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Review

Trends in LPWAN Technologies for LEO Satellite Constellations in the NewSpace Context

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Abstract: This study applies satellite constellations in Internet of Things (IoT) communications, specifically within low-power wide-area network (LPWAN) technologies in the NewSpace context. It comprehensively categorizes and describes the functionality and typology of low Earth orbits (LEOs), examines the societal impacts of these technologies, and provides an in-depth analysis of IoT communication architectures and protocols utilizing satellites. Additionally, the study identifies and addresses the challenges faced in this domain while highlighting future trends and developments. By collating and synthesizing pertinent information, this research offers a thorough overview of the opportunities and challenges in this evolving field of study.

Keywords: satellite; communications; IoT; NewSpace; LPWAN; LEO

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1. Introduction

NewSpace represents a modern approach to space missions, characterized by three main elements: space privatization, satellite miniaturization, and the development of innovative services utilizing space data [1]. This concept diverges from traditional government-led space programs, emphasizing the role of private companies, like SpaceX and Rocket Lab, in satellite manufacturing and launching. The adaptation and screening of Commercial of The Shelf (COTS) components boosted the miniaturization of satellites, including cube, micro-, and nanosatellites, enabling deployment in a single launcher and facilitating more accessible access to low Earth orbits (LEOs) [2].

Satellites in LEOs, orbiting between 160 and 2000 km above Earth's surface [1], offer various services. These include Earth observation, Internet connectivity, scientific research, satellite navigation, integration with 5G technology, and tracking for aeronautical and maritime purposes. These services result from the combined effects of space privatization and the trend toward smaller satellites [3].

NewSpace has catalyzed the emergence of the Satellite Internet of Things (IoT), enabling direct data collection from terrestrial sensors through compact, yet efficient, LEO satellites [4]. Previously, such data gathering would necessitate an extensive network of Earth stations. However, NewSpace advancements have facilitated cloud-based services that provide shared ground station networks and advanced computing capabilities for data processing. Furthermore, LEO constellations are transforming IoT connectivity, particularly in remote regions, with companies like FOSSA Systems, Sateliot, or Lacuna at the forefront of this development. The advent of satellite-based low-power wide area networks (LPWANs) marks a significant evolution in the IoT landscape, offering global connectivity to devices at costs competitive with terrestrial providers, thereby promising a substantial expansion of connected devices [5].

IoT is revolutionizing various industries by enabling connectivity across various devices, from sensors to autonomous vehicles, automating and enhancing operational processes. The advent of LEO satellite networks has broadened the connectivity possibilities for IoT devices in remote or isolated regions. It is a supplementary connectivity option in areas with terrestrial IoT networks. However, satellite IoT communications have challenges, including managing many devices, interference issues, and security concerns. Addressing these challenges is essential for the efficient and secure functioning of IoT satellite networks [6–9].

NewSpace's emergence has notably transformed the space industry, increasing accessibility for various players [10]. The space economy is on a consistent growth trajectory, with forecasts suggesting a value ranging from several hundred billion to multiple trillion dollars by 2040 [11]. Concurrently, the IoT satellite market is anticipated to grow substantially, with expectations of its value escalating from USD 1.1 billion in 2022 to USD 2.9 billion by 2027 [12].

This survey employs a methodical and technology-focused approach to comprehensively analyze satellite IoT communications in the rapidly evolving NewSpace era, characterized by significant advancements in satellite technologies and their terrestrial counterparts, such as LPWAN. This study offers an updated, technology-focused analysis that surpasses previous surveys in scope and depth. It involves a critical comparison with previous works. For example, reference [5] presents a general overview of machine-type communication from space, treating the LPWAN as a subset and not fully engaging with the NewSpace specifics emphasized in this survey. Survey [13], at present several years old, does not incorporate the latest developments in the nanosatellite context addressed here. While discussing the applications, reference [14] does not delve into the technological intricacies as thoroughly as this study. Similarly, surveys [14–18] concentrate on specific applications or aspects within satellite IoT, such as smart grids or MAC protocols, but do not offer a comprehensive technological overview provided here. This survey uniquely addresses a gap in the systematic analysis of LPWAN protocols within the NewSpace architecture, a critical aspect for the future trajectory of satellite IoT communications.

Addressing this gap, this survey examines satellite constellations and their IoT applications, mainly focusing on LEOs. It introduces a fresh perspective on societal impacts, dissects the architecture and protocols enabling IoT via satellites, and scrutinizes their challenges. Notably, the findings highlight the potential of LoRa/LoRaWAN in LEO satellite communications within NewSpace, marking a significant step towards overcoming the current limitations and paving the way for a future of extensive IoT connectivity. While the convergence of these LPWAN and NewSpace domains is recognized, there is a significant knowledge gap in determining the optimal architectural and technological paths for this integration. This research addresses this by evaluating the potential challenges and future directions of various LPWAN technologies in satellite IoT. Doing so aims to establish a foundational understanding for guiding the subsequent research and development in this evolving field.

This work is structured to provide a comprehensive overview of the integration of satellite constellations in the IoT, beginning with Section 2, which delves into the role of satellite constellations in IoT. Section 3 explores various architectures and protocols that facilitate IoT communications via satellites, setting the stage for Section 4, where the challenges and limitations inherent in this integration are addressed. Section 5 presents future perspectives, highlighting the emerging trends and potential advancements. Section 6 illustrates practical applications through a series of use cases, demonstrating the real-world impacts and applications of satellite-enabled IoT. Finally, the conclusions are presented.

2. Satellite Constellations in IoT

Artificial satellites serve various functions, such as communications, Earth observation, navigation, and global positioning. However, a single satellite cannot provide global coverage simultaneously. To address this, satellite constellations, which consist of numerous satellites, have been developed to enhance coverage and ensure global reach [15].

A satellite constellation is a group of satellites working together under centralized control to achieve a common objective [19]. Positioned in complementary orbital planes and connected to global ground stations, these constellations aim to provide interconnected network capabilities for IoT communications. This design ensures that at least one satellite is visible in specific Earth regions, offering continuous coverage.

Each satellite has a specific role in an IoT communications constellation, collaborating to offer comprehensive global services. Utilizing advanced communication technologies, they connect with Earth-based users through various antennas, such as directional antennas, omnidirectional antennas, and satellite dishes, adapting to different used cases and environmental conditions. Advanced orbit control technology keeps satellites in the correct position in space. This involves the continuous monitoring of satellites from Earth and necessary adjustments to maintain their proper orbits [20].

Satellites in these constellations are strategically placed in different orbits, each optimized for specific tasks. The orbits, shown in Figure 1, include:

- Low Earth Orbit (LEO): Satellites in LEOs are located at altitudes between 160 to 2000 km above the Earth's surface. These satellites can provide constant global coverage due to their proximity and ability to orbit the Earth multiple times daily. They are primarily used for Earth observation, communication, and global positioning services.
- Medium Earth Orbit (MEO): Satellites in MEOs are located between 2000 and 35,786 km above the Earth's surface. They provide regional coverage and are typically used for satellite mobile telephone services, navigation, and global positioning.
- Geosynchronous Equatorial Orbit (GEO): Satellites in GEOs are positioned at a constant altitude of around 35,786 km above the Earth's surface and move at the same speed as the planet's rotation. This allows them to stay in a fixed location relative to a specific point on Earth. Communication and meteorological observation services primarily use this region for uninterrupted coverage.

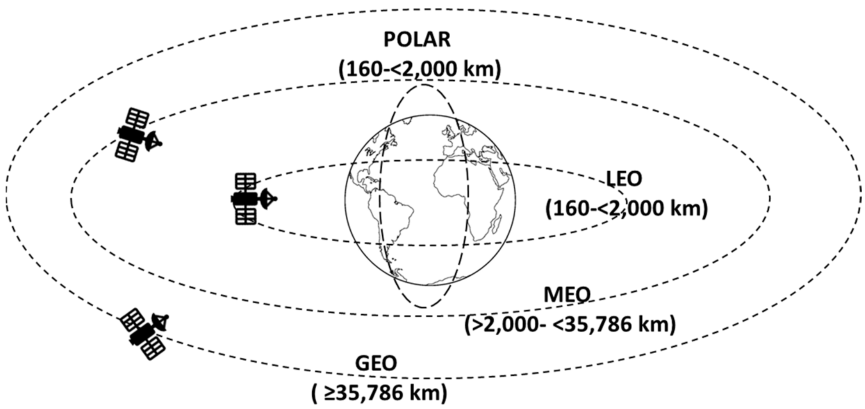

Figure 1. Types of orbits based on their orbital distances.

While advantageous for their reduced transmission power and ability to utilize smaller satellites, like CubeSats, LEO satellites face challenges. These include more satellites to cover larger areas and the Doppler effect impacting communications [21]. These challenges imply additional costs and complexities in designing and operating satellite communication systems.

Satellites are classified based on their application, orbit, and mass. The mass-based classification is the most common method (as shown in Table 1) due to its importance in determining the development and launch costs [22]. Large satellites have a useful lifespan of up to 10 years. They are designed for long-term operations, with redundant systems and electronic components resistant to space and cosmic radiation. They require more energy, which is generated by large photovoltaic solar panels. Due to their size, they are more complex to launch and require more powerful propulsion systems [22].

Table 1. Classification of satellites based on their mass.

Types of Satellites	Mass (kg)
Femtosatellites	<0.1
Picosatellites	0.1–1
Nanosatellites	01–10
Microsatellites	10–100
Minisatellites	100–500
Small Satellites	<500
Medium Satellites	500–1000
Large Satellites	>1000

The trend towards smaller, more affordable satellites is on the rise. Minisatellites weighing between 100 and 500 kg are becoming a popular alternative to large, expensive satellites. The miniaturized electronics in these satellites make them smaller and lighter, providing redundancy to ensure reliability. This miniaturization also reduces the launch costs, making it easier to launch them. Microsatellites weighing 10 and 100 kg are ideal for testing new technologies and capabilities before they are used for larger missions. They benefit scientific and exploration missions, where their small size and ability to be launched in groups provide flexibility and the capacity for simultaneous measurements at different points on Earth. The combined use of mini- and microsatellites is a growing trend in space exploration, providing a viable alternative to conventional large satellites.

Nanosatellites belong to the smallest satellite category, weighing between 1 and 10 kg. They are mainly used for technology demonstrations and educational missions due to their low cost, rapid development, and ease of deployment in small constellations. However, they are rapidly gaining popularity as an alternative to conventional satellites [23]. Among nanosatellites, CubeSats are the tiniest, measuring 10 cm × 10 cm × 11.35 cm and weighing less than 1.33 kg. Despite their small size, they include all the basic subsystems of larger satellites. Other satellite variants with even smaller sizes, such as PocketQubes, are also available [24].

Picosatellites weighing less than 1 kg are mainly used for technology demonstrations and educational missions. However, some satellite companies are presently using them to deploy low-cost constellations and offer commercial services. FOSSA Systems [25] is one such example. On the other hand, femtosatellites weigh less than 0.1 kg. They are primarily used for space fragmentation detection tests, the evaluation of tracking capabilities of various sensors used for space surveillance, and the detection of tiny objects [26].

The form factor, denoting a satellite's size and shape, is another classification criterion. CubeSats are measured in units (U), with 1U equivalent to a cube with an edge of 10 cm. This measurement is essential for planning and designing small satellites [24]. CubeSats are available in different sizes, ranging from 1U to 6U. However, even larger sizes, such as 12U and 16U CubeSats, are expected to be developed. Conversely, pocket tubes have an even smaller form factor than CubeSats [24].

Traditional Satellite vs. IoT Satellite

The satellite design for IoT communications has been comprehensively investigated in the scientific literature, providing invaluable insights into the efficiency and cost optimization. Ref. [24] focuses on adapting satellites for IoT applications, characterized by low data rates, within a bandwidth of approximately one hundred kilohertz. These satellites, characterized by their compact dimensions and straightforward hardware-like half-wave dipole antennas, need advanced functionalities, such as beamforming or inter-satellite links. Furthermore, they operate in lower frequency bands, like very-high frequency (VHF) and ultra-high frequency (UHF), aspects influenced by the prevailing scientific literature on communication hardware design.

In [27], scientific consideration is given to the efficiency and cost-effectiveness of small or nanosatellites. The proposal involves adopting 12U CubeSats arranged in a $2 \times 2 \times 3$ configuration, orbiting at 500 km altitude. This scientific configuration is presented as a balanced solution, aligning with the findings from the scientific literature, meeting both cost and service requirements, and allowing the periodic access of IoT terminals to the satellites.

Furthermore, ref. [28] outlines the hardware design considerations for IoT communication satellites. These considerations include the necessity for signal transmission and reception capabilities within suitable IoT application frequency bands, such as the L and S bands. Additionally, the requirement for antennas and signal processing systems enabling communication with IoT devices on the Earth's surface is emphasized. Given the substantial transmission distance in satellite communication, adequate power and signal amplification systems are essential to overcome increased path loss compared to typical terrestrial scenarios.

Moreover, IoT communication satellites must effectively manage data frame repetitions, involving the capability to receive, process, and retransmit data from IoT devices operating in conditions of deficient coverage. Consequently, satellites should be equipped with data storage and processing systems to handle frame repetitions efficiently, enhancing the probability of successful data transmissions from IoT devices [29].

Additionally, the critical differences with traditional communication satellites lie in the emphasis on miniaturization, commercial technology utilization, and cost-effective design philosophies. Unlike their traditional counterparts, IoT satellites prioritize compact form factors, simplicity, and scalability, aiming to support low-data-rate applications efficiently. Table 2 compares the main features of the two satellite communication solutions.

Table 2. Comparison between IoT satellite and traditional satellite communications.

Aspect	Satellite IoT Communications	Traditional Satellite Communications
Main objective	Facilitate connectivity among IoT devices and gather small volumes of data (e.g., sensors) to provide specialized services.	Provide global telecommunications services, such as television, telephony, and high-speed data transmission, to large audiences.
Type of transmitted data	Small data and control messages from IoT devices, such as sensors and meters.	Larger volumes of data, such as video, voice transmissions, and high-speed data.
Bandwidth	Lower bandwidth is required for transmitting low-speed and low-volume IoT data.	Higher bandwidth is required to handle high-speed transmissions and large data volumes.
Latency	Tolerant to higher latencies, as IoT data are often less time-sensitive.	Requires lower latency to ensure high quality of real-time transmissions, such as video conferencing and television broadcasts.
Network design	Oriented towards wide-area networks (WANs) to cover extensive geographical areas and connect distributed devices.	Designed for wide-area networks (WANs) or local area networks (LANs) to transmit data globally or regionally.
Power requirements	Focus on energy efficiency to meet the limitations of battery-powered and processing-constrained IoT devices.	Higher power supply capacity for traditional satellites and ground terminals with higher power requirements.

Table 2. *Cont.*

Aspect	Satellite IoT Communications	Traditional Satellite Communications
Number of connected devices	Scalability to support a large number of IoT devices scattered in different locations.	Less concern about the number of devices, with a focus on the quality and quantity of data transmitted per user.
Flexibility and configurability	Greater flexibility to adapt to different protocols and specific requirements of IoT devices.	More robust and specialized configuration to manage different types of telecommunications services.
Cost	Emphasis on cost-effective solutions to enable widespread adoption of IoT devices.	Higher budgets, as traditional satellite communication services, require a more complex infrastructure and powerful equipment.
Orbit type	Generally, LEO facilitates direct communication with IoT devices and reduces latency.	GEO or MEO to provide constant coverage over specific areas or regions of the planet.
Hardware components	Specialized transceivers and antennas for efficient communication with IoT devices.	More powerful communication equipment, including transponders, power amplifiers, and high-gain antennas, for long-distance signal transmission and reception.

3. Architectures and Protocols for IoT Communications via Satellites

3.1. Architecture

The IoT satellite communications stack model comprises five main layers that work together to collect and process data. The layers are:

- Physical layer: In this layer, the data are collected from the environment using IoT nodes with sensors, and the environment is controlled through actuators using wireless connectivity.
- Gateway layer: This layer consolidates data transmissions from IoT nodes. It includes satellite and terrestrial IoT gateways performing functions as communications gateways of the IoT nodes. A communication gateway is a hardware or software component that serves as an intermediary facilitating data exchange between disparate systems, networks, or devices. It plays a vital role in translating and managing communication protocols, ensuring compatibility and smooth data transfer between devices operating on different technologies or standards, as in IoT satellite communications.
- IoT network layer: This layer transports and transmits data to the middleware layer. This consists of the satellite network between the IoT nodes with the satellite, between the satellite and the ground station, and the terrestrial network between the ground station to the operator's cloud and from the operator's cloud to the business applications.
- Middleware or IoT platform layer: This layer receives the data transmitted by the IoT nodes and manages their processing. This consists of servers that act as middleware or IoT platforms, typically hosted in the operator's cloud that process, store, and forward satellite data to external applications.
- Vertical or business application layer: This layer uses the data received from the middleware layer to achieve a specific goal or purpose. They are applications that analyze and process data for specific business purposes.

The satellite IoT communications architecture for physical components is shown in Figure 2 and includes the following elements:

- IoT nodes: These devices, including sensors and actuators, facilitate wireless communication with satellites. Typically battery-operated, they can connect wirelessly to the satellite network and, in some cases, are compatible with terrestrial networks. IoT nodes are part of the physical layer in the IoT satellite communications stack model.
- Terrestrial IoT gateways: These gateways facilitate wireless communication for IoT nodes unable to transmit data to the satellites directly. They forward the data from the IoT nodes, facilitating the relay of data from the ground to satellites. Terrestrial IoT gateways are part of the gateway layer as they transmit and receive data from the physical layer.
- Satellites: Functioning as in-orbit gateways, these satellites collect messages from IoT nodes or terrestrial IoT gateways and retransmit them to the nearest ground station. Satellites are part of the gateway layer as they transmit and receive data from another layer, in this case, from the IoT network layer.
- Ground stations: These ground-based systems receive satellite data and forward them to the satellite operator's cloud for processing and storage. Certain stations are responsible for monitoring the health of satellites and controlling their functions. Ground stations are elements of the IoT network layer as they bridge the satellite and terrestrial networks.
- Operator cloud: This is where satellite data are processed, stored, and forwarded to external applications. The operator cloud belongs to the middleware layer in the IoT satellite communications stack model, and the satellite operating company typically owns it.
- Vertical or business applications: These applications utilize satellite data through the operator's cloud. They analyze and process the data for specific purposes, such as visualization. These applications are typically used in business contexts and are part of the business application layer.

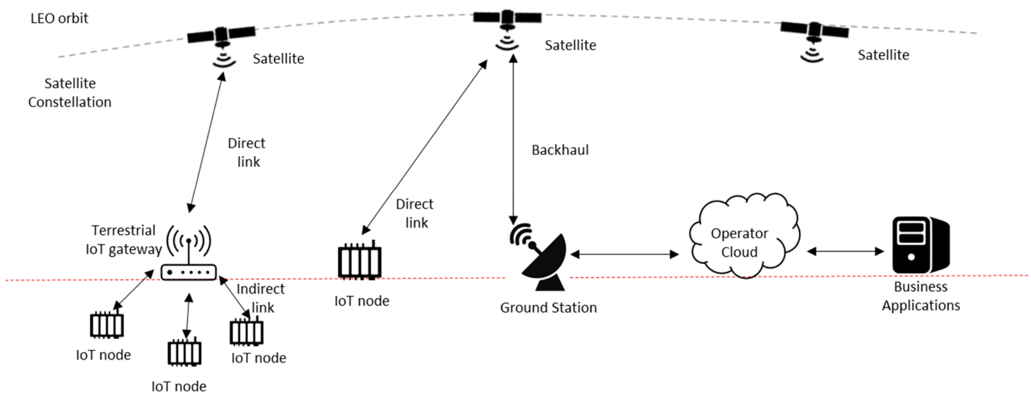

Figure 2. The physical architecture of IoT satellite communications.

When designing a satellite constellation, several key factors must be considered. These include global coverage, specific applications, individual satellite costs, and the overall constellation configuration. These considerations involve evaluating key parameters, like orbit eccentricity, altitude, and inclination, typically associated with low Earth orbits. Additionally, constellations can be designed with or without inter-satellite links (ISLs). Each satellite functions as a transparent relay in non-ISL constellations, channeling traffic from IoT nodes and ground stations to Earth. Conversely, satellites act as network switches in ISL constellations, enabling communication with neighboring satellites [28].

There are two primary approaches to the IoT network architecture in satellite constellations (illustrated in Figure 3): centralized and direct. In the centralized approach (Figure 3a), called the indirect-to-satellite IoT (ItS-IoT), ground-based communication gateways serve as intermediaries between the IoT node and the satellite. The terrestrial gateway relays data from the IoT device to the satellite. In the direct approach (Figure 3b), known as the direct-to-satellite IoT (DtS-IoT), the IoT device sends the data directly to the satellite [30].

In both cases, the collected data are transmitted to the ground station and delivered to a data repository or database for further processing by computer applications.

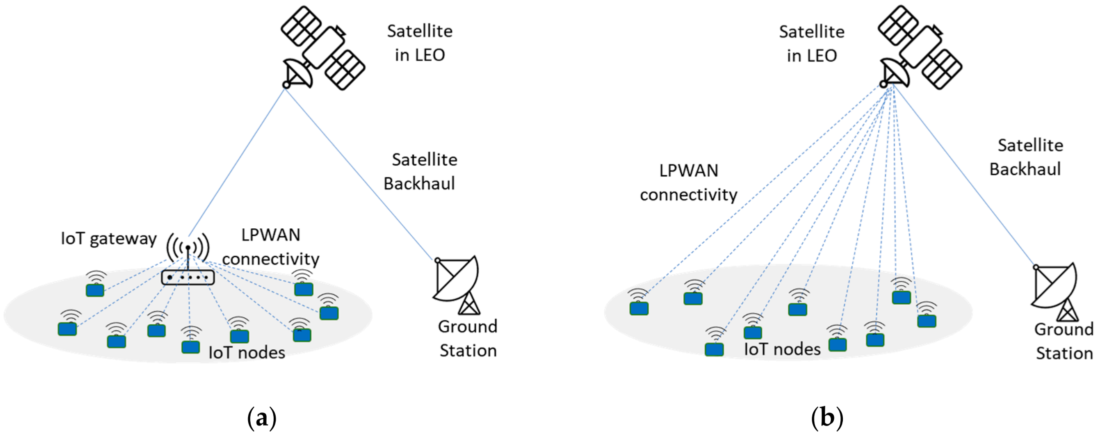

Figure 3. IoT communication architecture: (**a**) ItS-IoT and (**b**) DtS-IoT.

Table 3 highlights the primary differences between these two methods (DtS-IoT and ItS-IoT), clearly comparing their respective features and applications.

Table 3. Comparative summary between DtS-IoT and ItS-IoT.

Criterion	DtS-IoT	ItS-IoT
Connection	Devices connect directly to satellites.	Connection through terrestrial infrastructure, such as base stations or gateways, which then connect to satellites.
Communication Protocol	Uses specific IoT protocols for low-power and low-speed data transfers, like LPWAN protocols.	Can use a variety of communication protocols, such as cellular, sensor networks, and LPWAN protocols.
Coverage	DtS is suitable for areas lacking a terrestrial infrastructure or where it is temporarily unavailable.	ItS is more appropriate in densely populated areas justifying the deployment of dedicated IoT gateways [31].
Cost and Efficiency	Devices can be more cost-effective and efficient as they do not require an additional terrestrial infrastructure.	Can be costly and consume more energy due to a terrestrial infrastructure and communication through multiple links.
Development and Deployment	Can be easier and quicker to develop and deploy as they do not rely on a terrestrial infrastructure [32].	Can require more time and resources for development and deployment due to the need to build and maintain a terrestrial infrastructure.
Applications	DtS is especially useful in less accessible regions, like oceans, mountains, and poles, where deploying IoT gateways can be difficult or unjustified [31].	ItS is more suitable for dense urban areas with a high concentration of IoT devices [33].
Latency	DtS generally has lower latency as the data are transmitted directly from IoT devices to satellites.	iDtS involves data passing through terrestrial gateways before reaching satellites, potentially increasing the latency.

Table 3. *Cont.*

Criterion	DtS-IoT	ItS-IoT
Communication Channel	The communication channel between end devices and satellites is highly variable due to the movement of satellites in orbit. During a typical satellite pass, the channel conditions can change drastically.	The communication channel between end devices and terrestrial gateways is stable and predictable.

Compared to terrestrial IoT communications, implementing a satellite network in an LEO has significant differences. A key difference is the extent of coverage: terrestrial gateways typically cover only a few kilometers, whereas a satellite in an LEO can cover hundreds of kilometers. This disparity is influenced by several factors, including the satellite's orbital position, the transmission beam's shape and size, its distance from Earth, and the elevation angle, all of which affect the satellite's coverage area [34].

LEO satellites move at high speeds around the Earth, causing the footprint and transmission beam to move across the ground at thousands of meters per second. This generates a negative frequency distortion due to the Doppler effect, resulting in rapid dynamic changes in network connections and the number of service terminals. Additionally, terrestrial IoT nodes have a limited communication distance of several kilometers, while satellite IoT nodes have a signal transmission distance that extends to hundreds or thousands of kilometers. This extended range leads to significant transmission losses and delays, adversely affecting the energy consumption of IoT devices and necessitating specialized design considerations for communication protocols [35].

Cross-cutting any architecture, some authors have proposed improvements in the security and reliability of these communications by including new technologies, such as Artificial Intelligence (AI), Machine Learning (ML), and Blockchain. In this sense, the Machine Learning (ML) algorithms presented allow a more intelligent allocation of resources in satellite networks, dynamically adapting to changing traffic patterns, improving, among other things, average access, and improving congestion in satellite IoT networks [36]. This enhances the spectrum efficiency and contributes to latency reduction and bandwidth optimization. ML is fundamental in proactively detecting anomalies, allowing predictive maintenance that ensures connectivity continuity for IoT devices [37,38]. In addition, ML is used on the satellite to perform inference and training tasks of AI models, such as neural networks, with the objective of processing and analyzing the data collected by IoT devices intelligently and autonomously, without having to send all the data to a data center on Earth [5,39]. For its part, Blockchain technology implements a decentralized and transparent approach, which guarantees the authenticity of the data transmitted and stored by IoT devices [40]. Therefore, its use focuses on access control, privacy, and security authentication [41,42].

3.2. LPWAN

LPWAN protocols are considered an appealing choice for integrating terrestrial and space IoT technologies on a global scale [33]. These wireless networks use a variety of IoT communication protocols and are specifically designed to connect low-cost and low-power devices [43]. LoRa/LoRaWAN and Narrowband IoT (NB-IoT) are among the most effective protocols in LPWAN communications for satellite IoT communications. They offer low-cost, long-range connections and reduced energy consumption [44]. Recent research has demonstrated that direct links to satellites can be established using these protocols [33], allowing IoT nodes to communicate directly with satellites in orbit.

On the other hand, ItS-IoT communications involve IoT nodes communicating with gateways over IoT terrestrial LPWAN protocols. The gateways then forward the data from the devices to the satellites using specific space protocols, such as the Consultative Committee for Space Data System (CCSDS)-based low data rate telemetry and telecommand protocols. Finally, the satellites retransmit the data to central network servers [33] in the operator cloud.

Many companies are incorporating LoRa and NB-IoT technologies into their satellite systems to ensure the widespread availability of IoT services via satellite constellations in LEOs. This combination of satellite and LPWAN offers extended coverage and the opportunity to increase network reliability and capacity. Lacuna Space, Thuraya, and Wyld Networks stand out among these companies, using LoRa connectivity in their developments—other companies, like Sateliot, Ligado, and GateHouse, for NB-IoT [44].

LPWAN communications protocols are gaining significant attention due to their ability to offer affordable connectivity to low-power devices [43]. These communications include connectivity protocols in both licensed and unlicensed bands. The protocols that operate in licensed bands conform to the regulations established by the 3rd Generation Partnership Project (3GPP), an organization responsible for standardizing mobile communication technologies, such as NB-IoT, LTE, and 5G [45]. However, LoRa or Sigfox are protocols that 3GPP does not standardize.

According to [43,46], LPWAN communication protocols have several significant benefits and characteristics, including low energy consumption, wide-area coverage, low cost, support for many connected devices, and simplicity in network topology.

3.2.1. NB-IoT

NB-IoT is an LPWAN communication technology created to enhance the performance of the LTE standard [47]. Its main objective is to support low-cost, low-power devices while improving the coverage. This is achieved using a narrower bandwidth, a single transmission subcarrier (3.75 or 15 kHz). This makes connecting low-transmission-rate devices easier and enhances the signal quality [44].

To expand the reach of NB-IoT and connect devices outside terrestrial networks, the 3GPP Release 17 framework presents the possibility of adapting it to be compatible with non-terrestrial networks (NTNs). Additionally, Release 17 has incorporated improvements that cover extending coverage, increasing service reliability, and utilizing NTN multicast and broadcast capabilities to enable and improve the scalability [48]. It focuses on the bent-pipe architecture, as it facilitates NB-IoT's integration into existing satellite-based NTNs with a transparent payload. As defined by the 3GPP, a transparent payload satellite is considered an advanced repeater capable of performing frequency shifts between the feeder link frequency band and the serving link frequency band, as opposed to a basic repeater [49].

The bent-pipe architecture is a technique widely used in satellite communications. In this mode, the signal received by the satellite is amplified, filtered, and retransmitted in real time to the ground station without any additional processing on the satellite. This architecture connects IoT devices in remote or hard-to-reach areas in satellite communications with the NB-IoT. Its architecture is implemented through a transponder, which receives signals from IoT devices operating in the NB-IoT frequency band and retransmits them to the corresponding ground station.

The NB-IoT architecture is built upon the existing cellular infrastructure, but it can be extended to connect devices beyond the range of terrestrial networks. This is achieved by applying NB-IoT adaptation to support NTN, like satellite communications. Release 17 focuses on the "bent-pipe" architecture, which enables NB-IoT's integration into existing satellite-based NTNs with a transparent payload. This is performed by integrating NB-IoT into the operator's network core, as shown in Figure 4. It is the central part of the network infrastructure responsible for managing and controlling device communications. This architecture is implemented through a transponder that connects IoT devices in remote or hard-to-reach areas [48].

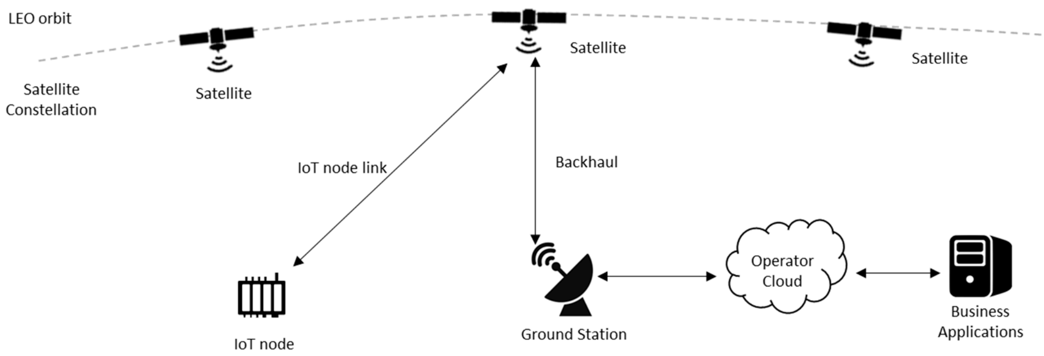

Figure 4. NB-IoT architecture for satellite communications in an LEO.

In practical terms, as shown in Figure 4, the communication process in IoT devices takes place in the following steps: firstly, the IoT devices located in remote or hard-to-reach areas transmit their data through the NB-IoT protocol to the satellite close to them. The satellite then acts as a relay and forwards the data to the ground station. This ground station is a crucial part of the NB-IoT infrastructure owned by the operator. Once the ground station receives the datum, it is integrated into the NB-IoT network and operator cloud and forwarded to the end-user's business applications.

Sateliot has designed IoT satellite hardware for NB-IoT, emphasizing several crucial aspects. Firstly, they employed a multi-beam approach to ensure broad coverage and an increased capacity. This approach requires using multiple radiofrequency fronts and antennas pointed in different directions or more complex antennas with beamforming capabilities. Secondly, the link design, including the link budget and beam arrangement, was analyzed with specific considerations for antenna gain, polarization, temperature, and user equipment noise. The design also addressed other essential adaptations for operation in low-density satellite constellations, such as discontinuous service operation, feeder connectivity, time and frequency synchronization, time relationships, and mobility in idle and connected modes [50].

3.2.2. LoRa/LoRaWAN

The LoRa connectivity protocol, patented by Semtech, enables long-range communication links [51]. It operates in unlicensed bands within the industrial, scientific, and medical (ISM) bands using a modulation technique called the chirp spread spectrum (CSS) at frequencies below 1 GHz, such as 169 MHz, 433 MHz, 868 MHz (in Europe), and 915 MHz (in North America) [52]. The LoRa protocol's physical layer is proprietary and establishes the basis of communication, while LoRaWAN is an open medium access layer (MAC) specification based on the LoRa physical layer.

LoRa technology offers six orthogonal spreading factors (SFs), ranging from SF7 to SF12. The choice of SF directly impacts the data transmission rate, transmission distance, and resistance to interference [53]. The SF value determines the transmission duration of a data packet and the transfer rate, affecting the appropriate choice of SF for a given scenario.

The LoRa frame structure consists of three main parts: the preamble, the header, and the message payload [54]. The LoRaWAN specification defines three different device classes, Class A, Class B, and Class C, each with its unique transmission and power consumption characteristics [53,55,56].

In terms of security, LoRaWAN uses the AES128 encryption and provides two options for connecting devices to the network: over-the-air activation (OTAA) and activation by personalization (ABP) [57].

The long-range frequency-hopping spread spectrum (LR-FHSS) is an enhancement of LoRa that aims to improve the capacity and reliability of LoRa networks in high-device-density and data-traffic-congested environments [58]. The LR-FHSS provides more flexibility and scalability, offering adjustable data rates. It utilizes a rapid FHSS modulation and spread spectrum, which reduces interference and enables long-range communication. This technology is an excellent candidate for implementing dense and long-range networks in the context of satellite IoT, and it has been developed to enhance network capacity and collision resistance [59]. It is used in satellite constellations, like Echostar, and has also been adopted by Lacuna, which initially used terrestrial LoRa with CSS [60]. The LoRa Alliance has endorsed the development of LR-FHSS as a crucial extension of LoRa for long-distance applications [59]. Table 4 shows a comparison between LoRa and NB-IoT for satellite communications.

Table 4. Comparative summary between LoRaWAN and NB-IoT for satellite communications.

Criterion	LoRa/LoRaWAN	NB-IoT
Definition	A low-power, wide-area networking technology for IoT.	A low-power cellular network technology for IoT, based on LTE.
Satellite communications	Yes, with CSS and LR-FHSS.	Yes. From Release 17 of 3GPP.
Frequency	Operates in license-free ISM bands.	Uses licensed LTE frequency bands.
Bandwidth/speed	Limited bandwidth; low data rates.	Limited bandwidth; low data rates.
Energy consumption	Very low.	Low, generally higher than LoRaWAN.
Cost	Lower due to the use of unlicensed spectrum and less expensive hardware.	Higher due to licensed spectrum and more sophisticated hardware.
Applications in NewSpace	Ideal for remote sensors and IoT devices in small satellites and isolated locations.	Ideal for remote sensors and IoT devices in small satellites and isolated locations.
Companies using it	IoT and NewSpace companies, like Lacuna or Fossa Systems.	IoT and NewSpace companies, like Sateliot or Ligado Networks.
Advantages	Low cost, low power consumption, ideal for low-bandwidth IoT devices.	Low cost, low power consumption, ideal for low-bandwidth IoT devices.
Disadvantages	Bandwidth and speed limitations; dependent on LoRa network coverage.	Higher cost and energy consumption; dependent on a licensed spectrum.
Standards and regulations	Complies with ISM standards; regulations vary by region.	Based on LTE standards; telecommunications regulations.
Security and encryption	Integrated security protocols, but less robust than NB-IoT.	Robust security, advanced encryption, authentication.
Interoperability with terrestrial networks	Compatible with terrestrial networks, but uses an LR-FHSS modulation.	High interoperability with existing terrestrial networks from Release 17.
Scalability	It supports a large number of devices, including millions in a satellite constellation, making it highly scalable.	It supports a large number of devices, including millions in a satellite constellation, making it highly scalable.
Latency	Higher latency compared to NB-IoT.	Lower latency, suitable for applications requiring a quick response.
Resilience and reliability	Good under ideal conditions, varies with the environment, and can be affected by interferences as it uses non-licensed bands.	Very high as it uses licensed bands.

Table 4. *Cont.*

Criterion	LoRa/LoRaWAN	NB-IoT
Implementation models	Private or public satellite networks, dependent on LoRa network coverage and local or regional regulations.	Implementation of satellite networks via cellular network operators, private or public networks, but uses licensed bands.
Appropriate use cases	Suitable for NewSpace applications where low power consumption and low cost are crucial, such as remote monitoring and sensors on small satellites or isolated ground stations.	Preferable for applications that require greater bandwidth and reliability, such as large-scale data transmission or IoT devices in areas with good cellular coverage.
Innovations and trends	Continuous developments in energy efficiency and range.	Advances in integration with 5G; improvements in speed and capacity.

The LoRaWAN is a communication protocol widely used in IoT applications. In this protocol, a LoRaWAN network server (LNS) manages devices connected to the network. The LNS collects device data, contextualizes them, and prepares them for use in business applications and IoT platforms.

The communication process in IoT devices occurs in several steps, as shown in Figure 5. First, the IoT devices send data periodically to orbiting satellites. These satellites act as relays that forward the information to ground stations. Within the operator's cloud, three crucial components facilitate the efficient functioning of the LoRaWAN network. The network server manages devices, security, and monitoring to ensure the seamless integration of satellite-relayed data. The application server interprets and processes these data for various business applications. The join server handles the incorporation of new devices, focusing on authentication and security. Together, these components create a comprehensive architecture that extends the connectivity of the LoRaWAN. This ensures that the relayed IoT data reach end-users' business applications effectively.

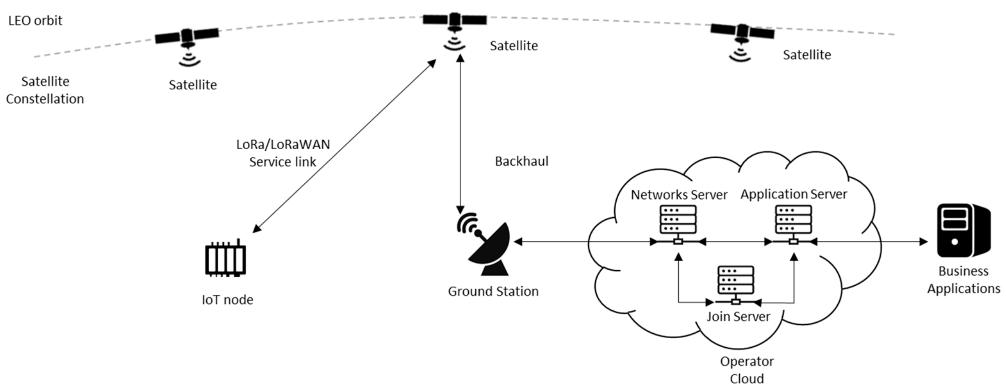

Figure 5. LoRaWAN architecture for satellite communications in an LEO.

The implementation of this architecture can differ in various satellite constellations under development. Currently, four different models are being implemented with LoRa:

- DtS-IoT model with satellites in LEOs: IoT nodes connect directly to satellites in LEO orbits, as seen in the Lacuna or Astrocast constellations [60].
- ItS-IoT model with satellites in LEOs: IoT nodes connect to a terrestrial gateway and retransmit data through a satellite constellation in an LEO. FOSSA Systems and Swarm use this model.

- DtS-IoT model with satellites in GEOs: IoT nodes connect directly to satellites in GEOs in this model. Echostar uses it along with S-band LR-FHSS to communicate with GEO satellites [60,61].
- ItS-IoT model with satellites in GEOs: IoT nodes connect to a terrestrial gateway, retransmitting data through other satellite connectivity options. Inmarsat uses this model [5].

For some satellite IoT operators, such as FOSSA Systems, the hardware design of its IoT satellites for LoRa is founded upon a complete COTS architecture, utilizing a single AVR microcontroller and commercially sourced components. These satellites are configured in the PocketQube format, featuring dimensions of 5 $\times$ 5 $\times$ 5 cm and weighing less than 250 g. The design process prioritized the implementation of an agile and iterative methodology, mitigating potential points of failure and leveraging lessons learned from previous endeavors [25]. In addition, FOSSA has developed a new satellite generation, FOSSASat FEROX, aimed at providing secure, accessible, and reliable IoT communications anywhere from LEOs and carrying custom payloads for constellations [62].

3.2.3. Doppler Effect

The Doppler effect is a physical phenomenon that causes the frequency of a signal to change when the source, such as a satellite, moves relative to the receiver or IoT node on the ground. This frequency shift can impact the quality and reliability of the communication [13], making it essential to implement compensation techniques at the receiver. This effect is crucial in configuring and parameterizing satellite-based IoT communications for LoRa and NB-IoT technologies.

In the realm of LoRa, it is essential to account for the Doppler effects, particularly in LEO satellite connections. Variations in satellite speed relative to terrestrial IoT devices can introduce Doppler shift and rate challenges [63]. Study [63] suggests that a frequency of 433 MHz is particularly effective, offering enhanced stability and reliability and achieving a 100% packet delivery rate in specific scenarios. In contrast, higher frequencies, such as 868 MHz and 2.1 GHz, are more prone to the Doppler effect, potentially reducing communication reliability. This is especially true under certain spreading factors and bandwidth conditions. For example, a smaller spreading factor and frame length improve the transceiver's immunity to the Doppler effect when using COTS LoRa chips in LEO satellites [64]. Operators of LoRa Satellites need to consider the Doppler effect carefully, optimize for a Low Data Rate Operation (LDRO), and strategically select critical parameters, including bandwidth, carrier frequency, and satellite orbital height. These steps are vital for ensuring robust and reliable communication in LoRa satellite networks, particularly in the dynamic environment of LEO satellites.

Likewise, the Doppler effect is critical for NB-IoT, especially in LEO satellites with lower orbits and higher relative velocities [65]. This effect significantly influences signal quality, requiring precise tuning of crucial communication parameters. The study in [64] highlights specific parameters for direct connectivity to LEO satellites, such as a 2.2 GHz carrier frequency and the adoption of Orthogonal Frequency Division Multiplexing (OFDM) in the downlink and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink, using a narrow 180 kHz spectrum. This research underscores the significant impact of the Doppler effect on NB-IoT connectivity in lower orbits. It emphasizes the need for adaptations in receiver architecture, management of propagation losses, and power adjustments based on satellite-terminal distances.

4. Challenges and Limitations

Understanding the challenges and limitations of satellite IoT communications is crucial for developing effective strategies that maximize their potential and opportunities. The significant hurdles involved in this area are as follows:

- Real-time and critical communications: IoT communications using LPWAN technology are unsuitable for applications requiring critical or real-time communications. This limitation also applies to IoT satellite communications. In LEOs, constellation satellites intended for this purpose are only sometimes available in all Earth regions. This results in significant delays due to the datum's travel distance from the IoT device to the satellite and its final destination [66]. These delays can be critical for applications, such as health monitoring or public safety [5].

- Limited bandwidth: Despite the technological advancements, the bandwidth available in satellite IoT communications remains limited compared to terrestrial communications. This can hinder the efficient transmission of large volumes of data generated by IoT devices. Furthermore, bandwidth sharing among multiple users and applications can lead to congestion, affecting the quality of the service.
- Limited coverage: Although LEO satellites can offer global coverage, their presence in specific areas can be limited compared to terrestrial networks. This can result in areas with no or intermittent coverage, affecting the connectivity and availability of IoT devices [67].
- Interference: Satellite communications can be impacted by natural and artificial electromagnetic interferences. Solar storms can influence the quality of satellite communications [68]. Meanwhile, signals from other satellites [69] or terrestrial sources [13] can generate interferences that affect the reception and transmission of data, leading to a degraded signal quality and increased error rates.
- Security and privacy: Satellite signals can be captured by any receiver on Earth, raising concerns about the confidentiality and integrity of the transmitted information. Implementing robust security measures in satellite IoT communications in LEOs is essential, especially with the increasing risk of cyber-attacks due to the broader adoption of satellite technology [9].
- Space debris management: The growing accumulation of space debris in orbit represents a significant challenge for satellite communications. Space debris increases the risk of collisions with satellites in orbit, which can damage or destroy equipment and endanger its helpful life [70]. Mitigation measures, such as designing satellites with collision avoidance capabilities and space debris removal programs, are necessary.
- Regulations on the use of frequencies: The ITU regulates access to and use of the radio frequency spectrum in satellite orbits. Compliance with these regulations is crucial to ensure the interoperability and operability of satellite IoT-based solutions.
- Scalability of connected IoT devices: As the number of IoT devices increases, the satellite communications infrastructure must efficiently manage the large data volume they generate [71]. This requires efficient media access control protocols and algorithms to manage the connectivity and communications of IoT devices on the satellite network.
- Core network function distribution: Deploying network functions in emerging satellite networks, especially those with sparse satellite constellations, presents unique challenges compared to traditional LPWAN architectures, like LoRaWAN and NB-IoT. In satellite networks, the assumption of constant space–ground connectivity, common in conventional setups, needs a re-evaluation. Adapting to this scenario requires a shift in network design, with crucial network functions reconfigured for distributed operations. This includes enabling autonomous operations on satellites when isolated from ground stations. Identifying which specific LoRaWAN and NB-IoT functionalities should be onboard satellite systems and which should remain on the ground are critical areas of research and development. This decision will significantly influence the effectiveness and efficiency of satellite-based LPWAN architectures in managing the unique challenges of space–ground network dynamics.
- Doppler effect: This phenomenon and its effects are explained in Section 3.2.3.

5. Future Perspectives

This section outlines the prevailing trends in and perspectives on IoT satellite communications, underscoring significant advancements and research areas. The critical areas of focus include:

- Global coverage: Satellite communications service providers have developed satellite constellations to offer global coverage, extending the reach of IoT to geographical regions where a constant coverage is not feasible due to technical or economic constraints [5].
- Cost reduction: Significant cost reductions are anticipated as satellite IoT communications technology and infrastructure continue to evolve. Like the impact of mass production and technological advancements in terrestrial LPWAN networks, these developments are expected to drive cost efficiencies in satellite IoT communications [33].
- Security and privacy: Cybersecurity in IoT satellite communications is increasingly relevant. Security measures should be considered from the initial stages of satellite design and production due to the higher adoption of satellite technology, which increases the risk of possible attacks [9].
- Energy efficiency: To promote the long-term sustainability of IoT projects, it is critical to develop technologies and protocols that reduce the energy consumption of IoT devices and extend battery life [72]. This aspect is particularly vital for low-cost, battery-powered devices in LEOs, a frequent component of IoT networks [44].
- Interoperability: While satellite communication is optimal in areas lacking terrestrial LPWAN networks, terrestrial communication remains preferable where such networks exist [73]. As a result, both terrestrial and satellite networks must coexist in IoT communications. This necessitates interoperability and the development of hybrid networks, which are expected to drive growth in the coming years [13].
- Integration with other technologies: Satellite IoT communications increasingly integrate with emerging technologies, like edge computing, artificial intelligence, and cloud processing, enabling advanced data analysis and real-time decision making [74].
- Specific applications: Various industries, including logistics, agriculture, energy, environmental monitoring, asset tracking, and disaster and emergency management, stand to benefit from this technology. It offers global connectivity and the capability to monitor and control devices in remote or cellular coverage-deficient locations.

6. Use Cases

The emergence of IoT satellite communications has led to a wide array of use cases, especially in remote areas or regions without cellular coverage. Satellite connectivity remains the only viable option for transmitting data in such scenarios. These use cases involve IoT devices that monitor physical parameters and transmit information through IoT satellite communications. The primary use cases, as documented in [54,75], encompass:

- Smart agriculture: IoT sensors monitor the water level, temperature, fertilizer concentration, humidity, and several other parameters [72], allowing farmers to optimize resources and increase production. Furthermore, it enables the monitoring of the health status of livestock [76].
- Health and telemedicine: Satellite IoT communication is also utilized for follow-up telemedicine, enabling the remote monitoring and treatment of patients in remote areas [77,78]. IoT devices monitor health, such as physical activity trackers, heart rate monitors, and diabetes tracking devices. They can be used in telemedicine to send data to doctors, facilitating diagnoses and treatments.
- Smart cities: IoT satellite communication can provide ubiquitous IoT connectivity, ensuring that smart city applications can access reliable and consistent connectivity regardless of the location [79]. This ensures that critical services and applications, like disaster warnings, fire detection, and backup communications, remain operational, even during disruptions and can ensure continuous service within designated coverage areas, providing uninterrupted connectivity for Smart City applications. Satellite communication systems exhibit strong resistance to destruction, making them reliable in scenarios where traditional communication infrastructures can be vulnerable [80].
- Private security and public defense: IoT-based security systems employing sensors for monitoring play a pivotal role in both private and public defense systems. These

systems are adept at safeguarding homes, buildings, and even border areas [81] by alerting property owners or law enforcement agencies in the event of criminal activities. Furthermore, they significantly enhance regional surveillance and public safety [31].

- Transportation and logistics: IoT satellite communication is used in fleet management [82], vehicle [72] and container tracking, ship tracking, and traffic control [83]. This improves road safety and optimizes transport logistics.
- Environment and conservation: IoT is utilized for monitoring the environment in remote or protected areas, detecting fires [84], and monitoring water and atmospheric quality [51,85]. Furthermore, it allows for tracking wild animals, which can aid in wildlife protection and habitat restoration efforts [86].
- Energy and control of natural resources: This application utilizes IoT to generate, distribute, and monitor renewable energy plants [87] or critical infrastructures (e.g., bridges, dams, and power stations) [88]. Devices include energy meters, wind turbine sensors, and gas pipeline monitors [89].
- Infrastructure and construction: This involves monitoring maritime infrastructure, construction machinery and personnel, railway operations, and linear construction. These applications involve monitoring corrosion, flood and humidity, structural integrity, vital signs, localization, performance, staff activity, mass properties, and environmental factors, such as oxygen levels, toxic gases, soil quality, and pollution [90].

7. Conclusions

The space industry is experiencing a significant transformation, leading to a highly competitive and innovative environment driving progress in the sector. A leading innovation in this transformation is using satellite constellations for IoT communications in low earth orbits, recognized for their potential to achieve global connectivity with low energy consumption results for devices. In this context, LPWAN networks have emerged as a practical solution for communication with satellites in LEOs. Specifically, LoRa technology shows promise in enhancing the scalability and transmission rate of connected devices in these communications.

However, several challenges and limitations that need addressing exist. These include improving the energy efficiency, enhancing the device processing capacity, and developing more efficient and secure communication protocols. Additionally, the scalability of connected IoT nodes and the optimization of communications are critical for improving power consumption, bandwidth, and overall performance.

Therefore, establishing a robust infrastructure and efficiently managing the increasing number of IoT devices is imperative. Optimizing communications is critical to leveraging the full benefits of global connectivity offered by satellites in IoT communications. Addressing these challenges is essential to fully capitalize on the advantages provided by global connectivity satellites in IoT communications.

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