76th International Astronautical Congress (IAC 2025), Sydney, Australia, 29 Sep-3 Oct 2025.

IAC-25-IAC-25,A6,IP,34,x101898

Internet-of-Things international University partnership actions for current and future Space Traffic Management and Space Sustainability research: the SMILE-IoT initiative

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Abstract

In the last few years, IoT (Internet of Things) technology has attracted increasing attention within the aerospace sector, as low-power communication systems originally designed for terrestrial networks are adapted for satellites and airborne platforms. These technologies open new opportunities for climate monitoring, resource management, and, in the long term, space traffic management.
To coordinate ongoing efforts in this field, the research group S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) from Sapienza University of Rome, has launched the SMILE-IoT initiative. The program involves partners from different countries and addresses diverse use cases, ranging from precision agriculture and ecosystem monitoring to satellite formation flying and space debris removal. Building on earlier CubeSat missions such as WildTrackCube-SIMBA and the upcoming CORAL-2U, the initiative is supported by the Rome Technopole Foundation and aims to consolidate university contributions to the IoT technology in the aerospace field.
In the context of this framework, a collaboration has been developed between the SMILE-IoT initiative and the ABEAR (Autonomous Balloon for the Exploration of the Arctic Region) project hosted at the Ecole normale supérieure-PSL's Laboratoire de Météorologie Dynamique (LMD). This collaboration aims to deploy LoRa-based communications on sensor-equipped atmospheric balloons and assess balloon-to-satellite link reliability, energy efficiency, and data transfer performance in the harsh Arctic environment. Despite being at an early stage, the results provide a tangible case study of how IoT concepts can evolve from terrestrial and airborne demonstrators to space applications.
The paper will first describe the SMILE-IoT initiative and its theoretical foundation, then present the Arctic LoRa balloon experiment as a representative example. It will finally discuss enabling technologies and future applicability to Space Traffic Management (STM), highlighting lessons learned and the role of university missions in developing scalable and practical solutions.

Keywords: IoT, LoRa, CSS, Network, STM

Nomenclature
S Receiver's Sensitivity
BW Bandwidth
SNR Signal to Noise Ratio
NF Noise Figure

Acronyms/Abbreviations
S5Lab Sapienza Space Surveillance and Space Systems Laboratory
LoRa Long Range
IoT Internet of Things
CSS Chirp Spread Spectrum
LEO Low Earth Orbit
NF Noise Figure
SNR Signal to noise Ratio

1. Introduction

In recent years, IoT applications have expanded beyond its traditional terrestrial applications and is attracting interest in the aerospace field [1,2]. Originally developed to interconnect network of small sensors and networks on the ground, IoT technologies are now being adapted for satellites [3,4] and airborne platforms [5]. This transition has been made possible by the availability of compact, low-power radios and communication chips that

https://doi.org/10.52202/083079-0101

naturally fit within the constraints of university missions, where size, mass, and energy requirements are stringent.

Academic institutions have become key players in this effort. Through CubeSat missions, stratospheric balloon flights, and the development of small experimental payloads, universities can test new communication strategies within relatively short development cycles. These platforms, although modest in scale, provide the right environment to explore IoT-based solutions, since such technologies are lightweight, energy efficient, and cost effective by design.

The range of possible applications is wide. In the near term, space-based IoT can support environmental and climate monitoring [6], precision agriculture [7], and wildlife tracking. In the longer term, it may also serve more space-oriented objectives such as coordinating nanosatellite swarms, enabling formation flying, or contributing to Space Traffic Management (STM). As a result, extending IoT principles into space is not only a technical challenge but also an opportunity to develop new mission concepts that may become essential in the future.

In this context, the S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) at Sapienza University of Rome, whose research activities focus on space debris observation, satellite optical characterization, autonomous cultivation experiments in orbit, and innovative mission concepts, [8–15] has launched the SMILE-IoT initiative. Supported by the Rome Technopole Foundation within the Sapienza – Rome Technopole call for internationalization, the initiative brings together seven universities and research partners from several countries, addressing both practical demonstrations and theoretical investigations. Topics include the development of digital twins for IoT performance evaluation and the integration of IoT with other sensing methods to improve mission accuracy.
An important part of the project is dedicated to Space Traffic Management (STM) themes, where IoT approaches can easily support mitigation for Radio-Frequency Interference (RFI) in congested environments [16], support navigation and trackability [17] and many other strategic objectives and topics.

In parallel, Ecole normale supérieure – PSL's Laboratoire de Météorologie Dynamique, is preparing a LoRa-based communication experiment in the context of the ABEAR project, whose aim is to deploy sensor-equipped atmospheric balloons in the Arctic region. The goal of the experiment is to validate the reliability, energy efficiency, and data transfer performance of IoT links in extreme environments, with the perspective of extending LoRa communication to balloon-to-satellite and eventually satellite-to-satellite communication. Although still under development, this project exemplifies how simple IoT concepts can be scaled up from terrestrial to airborne and, in the future, space applications.

This article presents the SMILE-IoT initiative and its scientific rationale, describes the ongoing ABEAR efforts, and discusses how university-driven IoT research may contribute to key enabling technologies and future applicability in the domain of Space Traffic Management.

2. The SMILE-IoT initiative

The SMILE-IoT project (Sustainable Space Missions and Innovative Low-Cost Experimentation) has been conceived in 2024 by the Sapienza Space Systems and Space Surveillance Laboratory to participate within the joint Sapienza and Rome Technopole call for "Internationalization" projects, whose aim was to enable networks or scientists within different target areas that could support major sustainability and science projects.

Specifically, SMILE-IoT, is focused on Space Sustainability, which can be conjugated towards different strategic objectives, such as the constitution of an international network for the joint evaluation of possible applications within IoT modules for the space operations sustainability. The project build on the previous experience of the S5Lab team in IoT mission, developed through the "WildTrackCube-SIMBA" [18,19], 1U CubeSat mission for the IoT-based tracking of wildlife in Kenya, developed at Sapienza University of Rome together with University of Nairobi, Machakos University and through a joint IAF – GK Launch Services call for a launch opportunity which was awarded in 2019 and executed in 2021.

The project involves seven universities in seven countries (Sapienza in Italy, Ecole normale supérieure-PSL in France, Kyushu Institute of Technology in Japan, Yonsei University in South Korea, Polytechnic University of Tirana in Albania, INTEC in Dominican Republic and UTP in Panama.

This paper will describe the project results mainly dealing with Space Sustainability, STM and IoT-based connection between vehicles.

3. The Technology Behind the Initiative

IoT refers to the concept of connecting large numbers of small, distributed devices that can collect, process, and transmit data with very limited power budgets. On Earth, this technology has already transformed sectors such as agriculture, logistics, smart cities, and industrial monitoring. At the core of IoT is the use of simple and low-cost communication protocols that allow large networks of devices to exchange information efficiently without relying on complex infrastructure.

https://doi.org/10.52202/083079-0101

This approach has enormous potential in space applications. Satellites and airborne platforms are typically constrained by mass, volume, power availability, and communication bandwidth. Instead of using heavy and power-hungry radios, IoT-based devices and protocols offer a more efficient solution. Their main advantages: low energy consumption, robustness against interference, and support for multiple devices sharing the same channel make IoT devices attractive for the development of future constellations, swarm coordination, and resource monitoring from space.

Among the various standard IoT technologies, LoRa has become a leading candidate. LoRa is based on the CSS [20] modulation scheme, which encodes information by varying the frequency of a chirp signal over time. This approach provides excellent sensitivity and robustness against noise, at the cost of a relatively low data rate. These features match well with the actual needs of space IoT. The focus is rarely on moving large volumes of data, but rather on sending small packets that must arrive reliably despite very strict limits the on power and link budget.

Another strength of LoRa is its flexibility. Parameters such as spreading factor, bandwidth, or coding rate can be tuned depending on the mission profile [21]. In practice, this means the same technology can be used for a short terrestrial link as well as for a longer balloon-to-satellite experiment. The main LoRa parameters are listed in Table 1.

Table 1. Parameters of LoRa communication

Parameters	Options
Spreading Factor (SF)	6 – 12
Bandwidth (BW) [kHz]	7.8 – 500
Coding Rate (CR)	1 – 4
Low Data Rate Enable (DE)	1 or 0
Cyclic Redundancy Check (CRC)	1 or 0
Payload (PL) [Bytes]	0 – 255
Preamble (S_{pre}) [symbols]	6 – 65535

As an example of the influence of these parameters, Fig. 1 shows two different LoRa signals with same bandwidth but different SF. The signal on the left optimizes the data rate with low SF, while the signal on the right optimizing the link margin to ensure good signal reception by having longer chirps with higher SF.

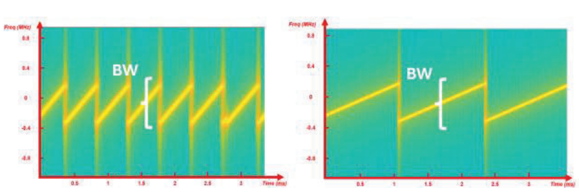

Fig. 1. SF comparison

By appropriately modifying all these parameters, it is possible to best adapt LoRa communication to the various mission scenarios according to the equation (1) that describes the receiver's sensitivity that is crucial to obtain the necessary link margin to achieve the communication:

$$S = -174 + 10log_{10}(BW) + NF + SNR_{min} \quad (1)$$

LoRa also benefits from an open and accessible ecosystem. Hardware is inexpensive, chipsets are compact, and the community of users is already wide, which makes it easier for universities to adopt and adapt the technology for experiments.

Because of this, IoT approaches, and LoRa in particular, are at the core of the SMILE-IoT initiative. They are not only a theoretical framework but also a set of practical tools that make it possible to design missions that stay lightweight and affordable, while at the same time exploring new concepts for aerospace applications and, eventually, space traffic management.

4. LoRa technologies for Arctic Monitoring: the ABEAR project

Monitoring the Arctic atmosphere is especially challenging because of the region's harsh climate and geographic remoteness. Current observational platforms include single-use weather balloons and tethered blimps, can sample only over the deployment location and, over the ocean, require deployment from an icebreaker [22–24].

An exception is the Controlled Meteorological balloon which, deployed from land, can perform up to a couple of days of sounding while flying over the ocean carried by the winds [25,26] .

The ABEAR project aims to overcome these limitations by 10 developing a rugged, sensor equipped, balloon-based observational platform designed to perform multiple soundings while flying autonomously across the entire Arctic basin over a couple of weeks km, one per day, from the Svalbard islands. To achieve an extended flight duration, the platform relies on state-of-the-art, lightweight material and sensors, as well as energy efficient control and communication systems. A simulation of achievable trajectories is shown in Fig. 2.

https://doi.org/10.52202/083079-0101

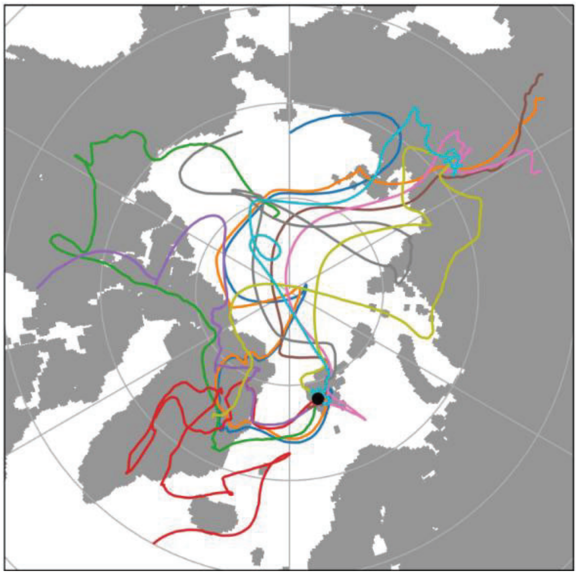

Fig. 2. Simulated trajectories of balloons deployed over ten consecutive days from Svalbard.

An important challenge in developing such a system is communication. As the platform goes quickly out of sight of ground stations, communication must be based on a satellite relay. LoRa has been selected as a candidate communication technology because it combines several advantages with respect to established satellite communication approaches: energy efficiency, simple lightweight and inexpensive hardware, and strong robustness against interference. Furthermore, LoRa modulation can handle Doppler reasonably well, which is a critical advantage in the context of satellite communication as the satellite is moving at several kilometres per second relative to the balloon.

Beyond a direct balloon-to-satellite link, LoRa enables the establishment of a balloon-to-balloon network. Each balloon could relay data from its neighbours, aligning well with the IoT concept. This setup would reduce the number of direct satellite transmissions, extend coverage to areas without satellite visibility, and conserve both power and bandwidth.

Preliminary tests performed using the WildTrackCube-SIMBA, LEO satellite developed at Sapienza, demostrated that ground-to-satellite communication is feasible. Several challenges had to be overcome to achieve this result: antenna polarization can reduce link quality; doppler shifts can move the signal out of the receiver's band, and long LoRa packets makes synchronization difficult. We overcome some of these challenges via hardware changes, and others by tuning the communication parameters, always trying to balance data rate with energy efficiency and reliability.

The lessons from these tests form the basis for the upcoming Arctic campaign. They suggest that the LoRa technology, while not designed for satellite communication in the first place, can be adapted to the balloon-to-satellite scenario. In the context of ABEAR, this means a chance to build a system that is both affordable and robust, supporting continuous monitoring of the Arctic atmosphere with limited resources.

5. Key Technologies for Space Traffic Management (STM)

The experience of the international network within IoT usage has highlighted possible applications of IoT for STM, space sustainability, and for traffic coordination aspects, which involve, as an example:

- Short range Inter-satellite link for collision avoidance, space-based traffic coordination, which could efficiently be managed through shared radio-frequency communication channels to decrease the workload upon STM entities;
- Active Debris Removal (ADR), where the coordination can happen with separate models, such as nano-tugs [27], to coordinate the grappling and removal manoeuvres;
- Formation Flying coordination, where the modules can be exploited for intra-constellation traffic coordination, by reducing possible RFI and by limiting the spectrum congestion.

Such technologies have been analysed in depth for application to STM, where the applicability appears immediate and critical to respond to the challenges posed by New Space to sustainability of the space operations.

6. Future Applicability

IoT-based communication is still at an early stage in the aerospace field, but some applications are already emerging. The ABEAR project aims to demonstrate how sensor-equipped atmospheric balloons combined with LoRa radios can monitor regions that are normally very hard to reach, like the Arctic. The energy efficiency of LoRa devices is central to achieving extended mission duration. The same approach could extend to global environmental monitoring, from climate and atmosphere to agriculture and resources.

A further development is represented by new missions such as CORAL, upcoming CubeSat developed by Sapienza University of Rome in collaboration with Thales Alenia Space Italia and Telespazio, aimed at LoRa for links between satellites. This is different from balloon-to-satellite communication and could be even more disruptive. If small satellites can talk to each other directly, they can share data without waiting for a ground station pass. That makes constellations more autonomous

https://doi.org/10.52202/083079-0101

and could also support longer campaigns with limited ground coverage.

7. Results and Discussion

The communication tests carried out with the CubeSat WildTrackCube-SIMBA have shown that LoRa can be used to send environmental data from ground devices or, as in this case, from atmospheric balloons directly to a LEO satellite.

In the tests, LoRa was the sole data link and demonstrated that it can support a direct-to-satellite telecommunication system, bypassing the ground devices or gateways typically required for LoRa when satellite connectivity is needed.

What makes this result interesting is its simplicity: a low-power configuration sufficient to transfer data via satellite link, overcoming the difficulties associated with distance and interferences. Indeed, LoRa is built to deal with interference and can tolerate the frequency shifts caused by fast satellite motion. Another point is that more than one device can transmit on the same channel, which opens the way to networks of balloons or sensors rather than isolated nodes.

This opens the possibility that balloons, ground stations, and satellites may operate together as a small network rather than acting as separate nodes. The tests with SIMBA therefore confirm that low-power IoT technologies can be adapted to space and can support scenarios where many small devices exchange and forward information. This perspective fits well with the idea of building scalable systems for continuous environmental monitoring.

8. Conclusions

The work presented here shows that IoT technologies, and particularly LoRa, can be used effectively in aerospace applications. Within the SMILE-IoT initiative, several partners are exploring how low-power communication can support different missions, from environmental monitoring to satellite coordination.

The trials carried out with the CubeSat WildTrackCube-SIMBA confirmed that LoRa can serve as the main communication link to a satellite in low Earth orbit. This is a key point for future campaigns such as ABEAR, where balloons drifting far from ground stations must still send back their data in a reliable way.

These first demonstrations suggest that small and inexpensive IoT radios, though originally designed for terrestrial networks, can be adapted to space conditions. They are energy-efficient, can handle interference and Doppler shifts, and allow several devices to share the same channel. Instead of acting as isolated elements, balloons or satellites could therefore operate as part of a wider network that grows with the mission.

Looking ahead, missions such as CORAL will extend this work by testing LoRa for inter-satellite links. Therefore, beyond climate and environmental monitoring, the same technologies demonstrated here lay the groundwork for future Space Traffic Management (STM) solutions. By supporting inter-satellite links, collision avoidance, and constellation coordination, IoT can directly contribute to the sustainability of space operations in the New Space era.

Acknowledgements

The SMILE-IoT project has been funded by the European Union - Next Generation EU – Mission 4, Component 2, Unique Identifier (CUP) B83C22002820006, in the framework of the Sapienza - Rome Technopole Call for Research Internationalization – Research Line 1.

The work concerning the ABEAR project for the study of the Arctic Boundary Layer has received support under the French Agence nationale de la recherche program ANR-22-CPJ2-0063-01 and the US National Science Foundation (NSF) project OPP-2413498.

The paper widely profits from the experiments done with WildTrackCube-SIMBA, supported by the Italian Space Agency under the agreement "Accordo Quadro n.2020-30-HH.0".

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