UAV and Satellite Employment for the Internet of Things Use Case

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Abstract—**Since the previous decades, the Internet of Things (IoT) is capturing a major interest and making critical changes in our life. It has been established in different sectors all over the world such as health-care, agricultural, logistics, etc. Long range transmissions and low energy consumption are two main features that IoT communication protocols should accomplish from a communication viewpoint. This led to the definition and deployment of a plethora of commercial or standardized solutions within the Low Power Wide Area (LPWA) category. From an architectural viewpoint, solutions to extend current network coverage are needed to allow IoT employment in all possible use cases. Unmanned Aerial Vehicles (UAVs) have witnessed exceptional growth and high demand in the IoT area. Besides, extending the number of supported devices and link capacity in urban areas and extending the coverage in rural and remote areas through satellite communication networks is envisioned as an improvement of the overall network infrastructure within the fifth generation of mobile communication (5G) framework.**
This paper presents a study of deploying an IoT communication protocol (LoRaWAN) gateway onboard a UAV communicating with the terrestrial network through a simulated satellite link. The aim of the study is to propose and test UAVs together with satellites as possible means to, on one hand, extend the coverage of LoRa network, and, on the other hand, offer a common solution to allow data exchange with multiple devices implementing different IoT communication protocols.

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1. INTRODUCTION

The spread of the Internet of Things (IoT) is increasing year after year, as well as the number of possible applications and use cases that can benefit from this technology. One of the 5G use cases defined by the International Telecommunication Union (ITU), called massive Machine Type Communication (mMTC), is mainly referred to as the IoT [1]. Typically, a very large number of devices per square kilometer need to transmit a low volume of non delay-sensitive data with energy consumption as low as possible.
However, offer connectivity to a so high number of devices which can also be located in rural and remote areas and with the required very low energy consumption can be a challenge for the classical telecommunication technologies, i.e. cellular and satellite.
Low Power and Wide Area (LPWA) technologies, such as LoRaWAN, SigFox, Ingenu, among others, are considered as a foreground solution to achieve the various requirements of IoT applications, especially to guarantee a very low energy consumption, with a transmission range of up to a few tens of kilometers, at the cost of low transmission rates.
Long Range Wide Area Network (LoRaWAN)[2] is one of the most used LPWA technologies in the IoT field, and it is already employed in a lot of different scenarios, such as smart industry, healthcare, traffic monitoring, and smart agriculture. However, a further drawback of these technologies is that they are proprietary solutions that require an ad-hoc access network (gateways), as shown in the LPWA layer structure in Figure 1, whose distribution is currently limited.

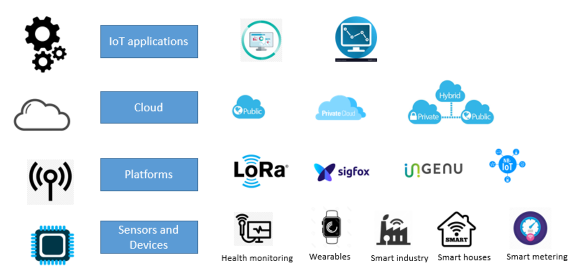

Figure 1: LPWA architecture layers.

Unmanned Aerial Vehicles (UAVs) are becoming popular and witnessing exceptional growth. Due to their high mobility and low cost, they have been used in several applications from military, such as for border surveillance, to almost all aspects of our daily lives, i.e. commercial applications such as packets delivery and photography. Moreover, they are experiencing very high demand in the IoT, where they are supposed to play a key role in some use cases, such as public safety, pollution and environmental monitoring, and smart agriculture [2].
In our proposed solution, the UAVs act as access nodes collecting data from IoT devices, such as sensors, in the areas where they are flying and delivering these data in real-time to the cloud platform aims to store, manage, and let the authorized users get access to them through a simulated satellite link. This idea has been already described in our previous paper [3], but in this work, we also present the testbed we developed in the meantime and the results obtained in the on-site tests.

We focused on the LoRaWAN technology equipping a UAV with a Raspberry Pi-based LoRaWAN gateway which also simulates typical delays and losses of different kinds of

[2]https://lora-alliance.org/

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satellite links (LEO, MEO, and GEO-based).
The remainder of the paper is organized as follows. Section 2 introduces the state of the art about the employment of UAV and satellite technologies in IoT applications. Section 3 contains a description of the network architecture of the commercial IoT communication solutions followed by a description of the reference scenario we have considered. Details about the developed test-bed are reported in Section 4. Obtained results are shown in Section 5, which confirm the feasibility of the proposed solution and highlight the differences with a more "classical" gateway deployment. Conclusions and possible future works are drawn in Section 6.

2. Related Work

IoT and UAVs

A well known environment that integrates these two technologies is *Smart Agriculture*. Traditional farming systems are transforming to what is known now as *"Smart Farming Systems"* by using sensing and networking technologies and Internet connectivity.
Monitoring and controlling crop parameters would help in improving the quality and quantity of food. This can be achieved by the integration of UAVs in the IoT field. Such work is presented in [4] where heterogeneous IoT devices are distributed in a crop field to sense environmental parameters and a UAV having a light weight energy efficient localization antenna is used to collect the generated data.
In [5], a smart agricultural monitoring system using LoRaWAN technology and UAVs is introduced. The aim of the study is to allow a LoRaWAN gateway attached to a UAV to fly over the fields and gather data from the ground sensors (temperature, humidity, and light sensors), thus helping farmers to get the needed information over a large, remote, and hard to reach farm field. Two different simulations were conducted at the parking building and the tree farm, respectively. In the first experiment, the data rate between the gateway and the sensor nodes was not affected if the position of the gateway changes vertically up to 15 m, but it decreases while moving the UAV horizontally. The real simulation was carried on in the tree farm, where the UAV flew over the ground sensors nodes verifying the one-to-many connection between the gateway and nodes. However, the authors couldn't know the maximum coverage of LoRaWAN due, on one hand, to the high power consumption of the UAV and, on the other hand, to the sensitivity of the gateway to the outside temperature.
An air quality monitoring system using LoRaWAN and UAV is presented in [6]. This system aims to monitor air pollution dynamically and effectively for environmental protection. LoRa-based PM2.5 sensors are implemented to sense the values and a LoRaWAN transmitter module is implemented on-board the UAV to collect the data and forward them to a cloud platform through a LoRaWAN gateway. The advantage of using a UAV is that it can send the sensed data to the server in real-time operating with minimal human intervention thanks to a route algorithm adapted by the authors. The demonstration results show the path followed by the UAV associated with the data gathered from each sensor node.
In [7], the authors use a UAV to gather data from sensors deployed on the ocean and then send these data to a base station to be analyzed. A security system able to control and monitor different sensors and actuators as UAVs is presented in [8]. Experimental results show the usefulness and effectiveness of such a system in ensuring home security. An evacuation system composed of IoT devices and UAVs is given in [9]. Such a system is controlled by an intelligent agent that is responsible for determining the best evacuating plan. A Raspberry Pi-bases system equipped on-board an aquatic drone which is connected to an array of sensors for air and the water-quality monitoring is presented in [10].

IoT and Satellites

The focus on the usage of satellite communication for the IoT is increasing [11], such as in environmental monitoring, emergency management, and smart grids. The integration of Low Earth Orbit (LEO) satellites in some IoT applications is becoming a new trend. Instead of using Geostationary Earth Orbit (GEO) satellites, LEOs are used as they provide lower propagation delays and lower losses. LEO satellites can be used as a powerful supplement for the IoT especially in, but not limited to, remote areas, due to the lack of proper coverage of the traditional terrestrial networks. To solve the problems related to remote sensing, such as the increasing system cost and the information analysis complexity, a LEO constellation-based IoT system is a possible solution. It will allow direct access to the information monitored by different types of sensors, ensuring more frequent data gathering than using a single sensing satellite and enhancing the prediction accuracy.
A water monitoring system example is proposed in [12], where the satellites are used to replace the traditional terrestrial network in unreachable locations such as wetlands and oceans.
In [13], the authors adapt the Information Centric Networking (ICN) concept. They introduce several models and evaluate them for IoT in hybrid satellite-terrestrial networks. The presented models aim to minimize the data and control traffic over a satellite network.
Maximizing the network throughput and reducing the energy consumption at the gateways is the aim in [14]. The authors formulated an online scheduling algorithm that allows them to efficiently collect all the data from the Geo-distributed IoT sensors via LEO satellites and send them to data centers to be analyzed.

3. Reference Scenario

Network architecture of commercial IoT solutions

Figure 2 shows a schematic representation of the network structure of all commercial IoT communication solutions.
Three are the main components of this network infrastructure: IoT devices, IoT gateways, and the IoT cloud platform. IoT devices, such as sensors and actuators, generate and send data towards the users linked to the Internet, or receive commands from them. To do so, they have to be connected to the Internet through intermediate nodes, called gateways, whose aim is to "convert" the communication protocols employed for the data exchange with the devices (usually low layer proprietary protocols) to the Internet stack protocols, in order to let the data packets travel through the Internet. The IoT cloud platform acts as an interface between users and devices: on one hand, all the data gathered by the devices are stored and managed in the platform, and, on the other hand, user-friendly interfaces are offered in order to let the users see these data and manage their own devices.

Considered smart agriculture scenario

In this framework, the scenario we have decided to focus our attention is the typical smart agriculture one. It is depicted in Figure 3.

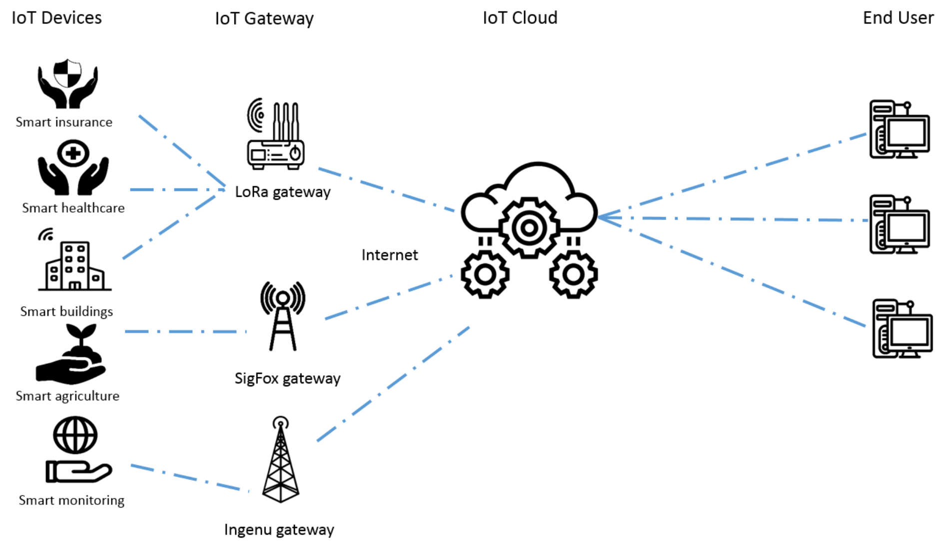


Figure 2: Long-Range IoT Commercial solutions architecture (icons are adopted from the Noun project website[3])

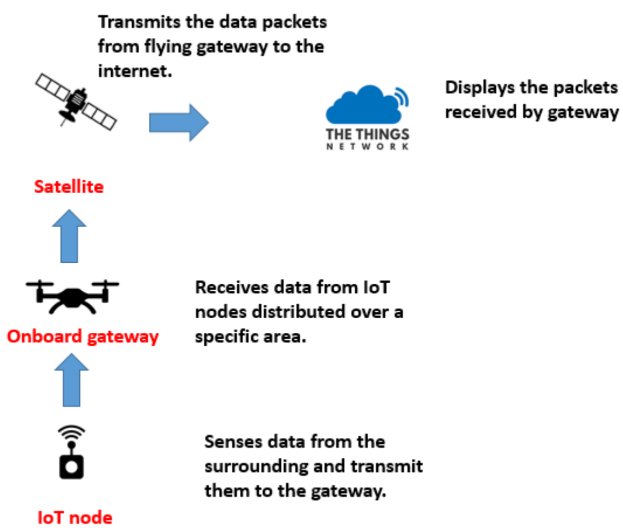


Figure 3: The considered scenario structure

There are some sensors of different kinds deployed in a wide area not covered by other terrestrial access technologies. Each sensor is equipped with a LoRaWAN transmission interface and they are all connected to a LoRAWAN gateway located within the maximum achievable transmission range (up to 15 km in rural areas). In our case, the LoRaWAN gateway is located on-board a UAV which keeps collecting data while flying above a certain area. To guarantee end-to-end connectivity, the UAV is connected to the Internet through a satellite link, which can be considered always active. In this way, each sensor periodically senses the environment generating one temperature, humidity, atmospheric pressure, or another kind of measurement which is received by the UAV-gateway and forwarded through a satellite until it reaches a LoRaWAN cloud platform, where an user can see it just opening a browser in his/her device.

4. Developed testbed

The testbed we developed to assess the feasibility of the proposed solution and to evaluate the obtained performance is structured as follows:

- IoT devices: we employed two devices like the one shown in Figure 4. They are based on an Arduino MKR WAN 1300 board and equipped with a temperature and humidity sensor (the first one with a DHT22 and the other one with a LM35) and an antenna to transmit in the license-free 863-870 MHz band, one of the two bands LoRAWAN devices can use in Europe.
- IoT gateway: the employed gateway is based on a Raspberry Pi 3 B+ equipped with the LoRa shield RAK2245 Pi-Hat (Figure 5). For the tests, the gateway was powered by a battery pack and has been attached to a UAV DJI Phantom as illustrated in Figure 6.
- Satellite: the presence of the satellite link between the gateway and the cloud platform has been simulated introducing delays and losses for the packets transmitted and received by the gateway in the Raspberry's operative system. In practice, the gateway is linked through its WiFi interface to an Access Point linked to the Internet through the cellular network.
- IoT Cloud platform: we exploited The Things Network (TTN), an open LoRaWAN cloud platform where we registered our devices and gateway and allow us to see the data coming from the sensors in real-time through its browser interface.

5. Performance evaluation

Before describing the obtained results, we just recall some details about the LoRaWAN packet transmission.
Figure 7 shows the communication process that is established between the IoT devices and the gateway before the nodes start sending data.

In the LoRaWAN solution, communications between devices and gateways are spread out over different frequency channels and data rates, affecting the achievable communication

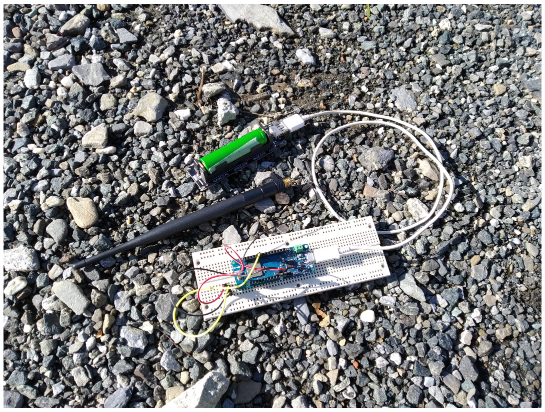


Figure 4: IoT devices based on Arduino MKR WAN 1300

Figure 5: IoT gateway based on Raspberry Pi and RAK 2245 Pi-Hat

Figure 6: UAV equipped with the IoT gateway

range and the packet transmission duration. The LoRa protocol, a chirp spread spectrum modulation technique, determines the amount of bits required to code the data (coding rate) and, consequently, the maximum achievable data rate. Each bit is encoded as multiple chirps and the relation between the bit and chirp rates may differ depending on the employed spreading factor (SF). Lower is the SF, higher is the achievable data rate. Table 1 shows the LoRa available SF.

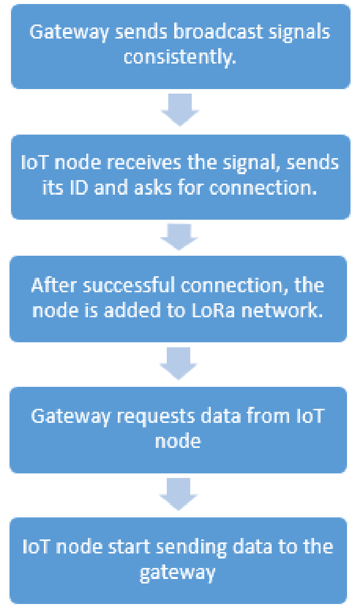


Figure 7: Communication between IoT node and gateway

Table 1: LoRa available SF for 125 kHz bandwidth channels

Spreading Factor (SF)	**Chirp/ symbol**	**SNR limit (dB)**	**Bitrate (bps)**
7	128	-7.5	5469
8	256	-10	3125
9	512	-12.5	1758
10	1024	-15	977
11	2048	-17.5	537
12	4096	-20	293

Each device dynamically selects its employed SF depending on the environment conditions and in order to offer the highest possible data rate and maximize both battery lifetime and communication range. In detail, each device computes the median Signal-to-Noise Ratio (SNR) of the last 10 received uplink packets and compares it with the limit SNR of each SF. This principle has to be taken into account since it affects some of the investigated performance variables.
On-the-field test has been carried out with the aim to confirm the feasibility of the proposed solution and assess the obtained performance in terms of different output parameters. During this test, two IoT devices have been placed in an open area at an approximate distance of 100 meters from each other. The UAV flew above the area at an altitude of 20 meters for approximately 20 minutes following a random path. During that time, each sensor keeps sensing the environment temperature and sending one packet every 30 seconds (due to the limitation imposed by the TTN Fair Access Policy).
Some of the obtained results have been compared with other results obtained from an in-the-lab test, where the gateway was located on a desk and its position was fixed.

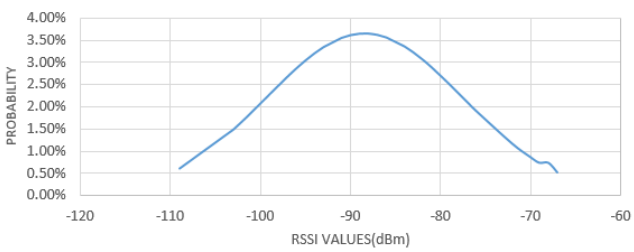
Signal Strength

After receiving data, the TTN displays different information about each received packet, as shown in Figure 8.

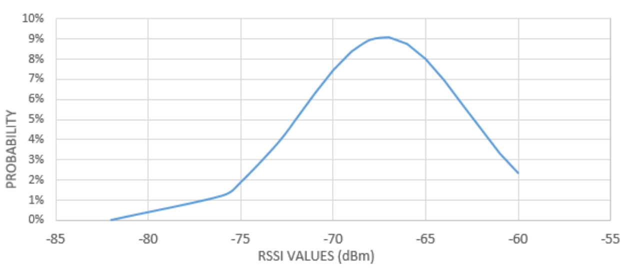

```
"payload": "QM0kASaAUQAE791Hd6/KOeg=",
"f_cnt": 81,
"lora": {
  "spreading_factor": 7,
  "bandwidth": 125,
  "air_time": 51456000
},
"coding_rate": "4/5",
"timestamp": "2019-10-16T10:15:10.098Z",
"rssi": -109,
"snr": 3.2,
"dev_addr": "260124CD",
"frequency": 867100000
```


Figure 8: Received packet information showed by the TTN

Received Signal Strength Indicator (RSSI) and SNR are two information the user can see among the others and allow to keep monitoring the quality of the channel between the devices and the gateway. Figures 9 and 10 show the density functions of the RSSI and SNR, respectively, obtained from both on-the-field and in-the-lab tests.



(a)



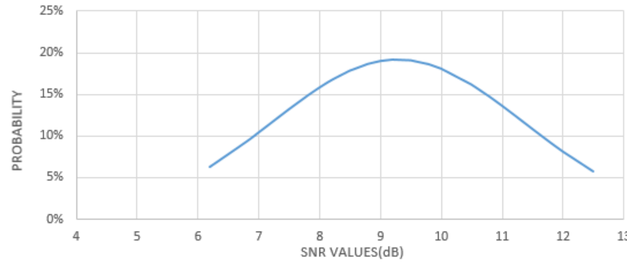
(b)

Figure 9: Density functions of RSSI values obtained from one-the-field (a) and in-the-lab tests (b)

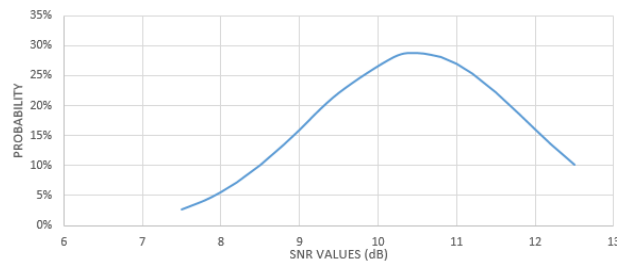
As expected, results obtained from the in-the-lab test show better channel quality, but it is optimal in both cases due to the presence of line-of-sight and low distances between the devices and the gateway compared to the maximum achievable transmission range. For this reason, the selected spreading factor is always the best one (SF=7).

Energy Consumption

One of the most concerned parameters dealing with the IoT and the UAVs is the energy consumption. We measured the current drained by the gateway from the battery pack through a current sensor. Figure 11 shows the density functions of the results obtained during the on-the-field test in terms of consumed current when the gateway is waiting for data and



(a)



(b)

Figure 10: Density functions of SNR values obtained from one-the-field (a) and in-the-lab tests (b)

when it is receiving and forwarding packets, respectively. Comparing these results with the one obtained during the in-the-lab test, shown in Figure 12, we obtained higher and more spread values in the on-the-field test, as expected, due to the higher and not constant distance between the gateway and the access point.

In some figures, the shape of the density curves seams incomplete due to the lack of a proper number of collected data, but in all cases, it is easy to see the obtained mean and standard deviation values, also reported in Table 2.

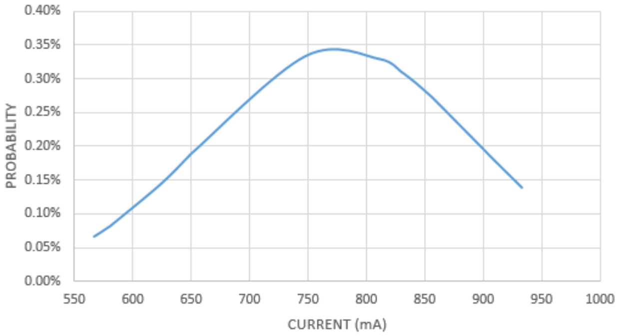
Table 2: Mean and standard deviation values for current consumption

	Mean (mA)	**Standard Deviation**
Current Waiting (in-the-lab test)	659	27.65
Current Peak (in-the-lab test)	1040	21.99
Current Waiting (on-the-field test)	776	116.04
Current Peak (on-the-field test)	1348	18.27

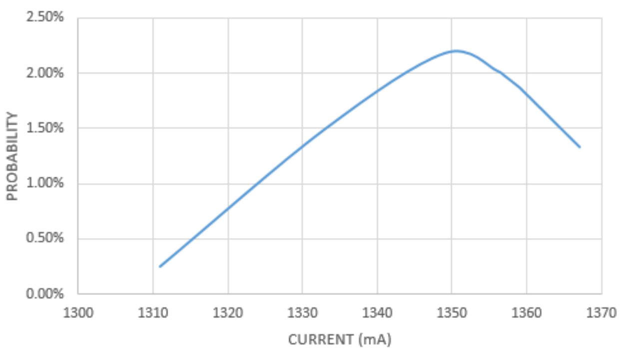
Losses

In order to simulate the loss of a satellite link, we performed some tests introducing 4 different loss values: 1%, 2%, 5%, and 10%.

Figure 13 shows a screenshot of the TTN interface where the loss of one packet is highlighted in the case of a 10% loss. We decided to not show the screenshots of the other 3 cases because the obtained losses follow the simulated values and do not give any additional information.

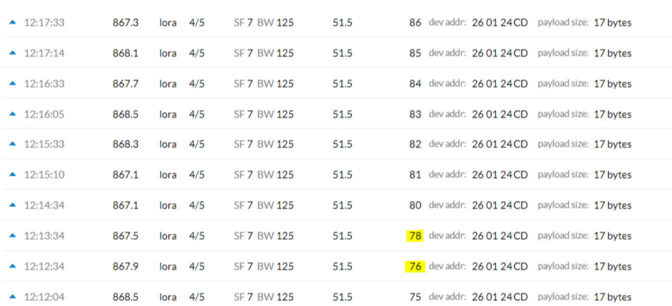


(a)



(b)

Figure 11: Density functions of consumed energy measured during the on-the-field test while waiting (a) and transmitting (b)



12:17:33	867.3	lora	4/5	SF 7 BW 125	51.5	86	dev addr: 26 01 24 CD	payload size: 17 bytes
12:17:14	868.1	lora	4/5	SF 7 BW 125	51.5	85	dev addr: 26 01 24 CD	payload size: 17 bytes
12:16:33	867.7	lora	4/5	SF 7 BW 125	51.5	84	dev addr: 26 01 24 CD	payload size: 17 bytes
12:16:05	868.5	lora	4/5	SF 7 BW 125	51.5	83	dev addr: 26 01 24 CD	payload size: 17 bytes
12:15:33	868.3	lora	4/5	SF 7 BW 125	51.5	82	dev addr: 26 01 24 CD	payload size: 17 bytes
12:15:10	867.1	lora	4/5	SF 7 BW 125	51.5	81	dev addr: 26 01 24 CD	payload size: 17 bytes
12:14:34	867.1	lora	4/5	SF 7 BW 125	51.5	80	dev addr: 26 01 24 CD	payload size: 17 bytes
12:13:34	867.5	lora	4/5	SF 7 BW 125	51.5	78	dev addr: 26 01 24 CD	payload size: 17 bytes
12:12:34	867.9	lora	4/5	SF 7 BW 125	51.5	76	dev addr: 26 01 24 CD	payload size: 17 bytes
12:12:04	868.5	lora	4/5	SF 7 BW 125	51.5	75	dev addr: 26 01 24 CD	payload size: 17 bytes

Figure 13: List of received packets highlighting one packet loss

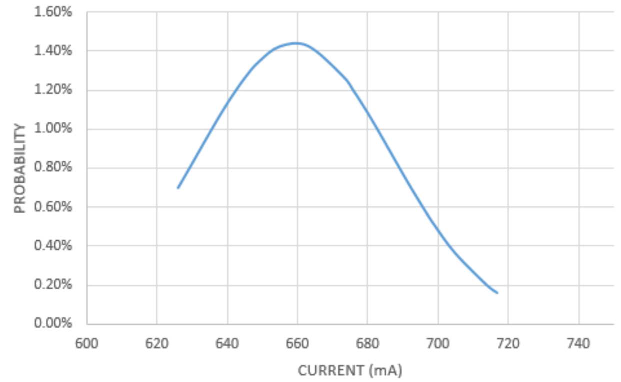
The gateway keeps forwarding data in all cases, which proves the robustness and tolerance of the system in case of the satellite presence in the path between the gateway and the cloud platform in terms of loss.

Delivery time

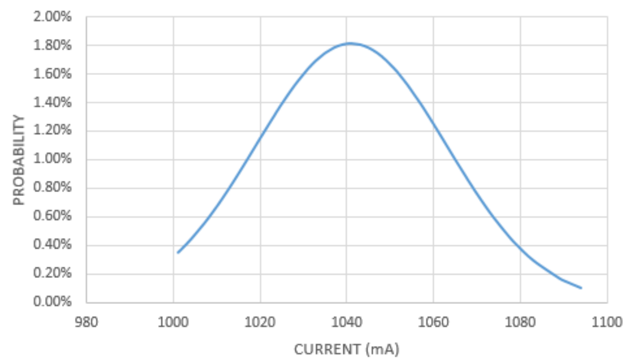
The delivery time of the end-to-end communication between devices and the cloud platform t_{ee} can be defined as:

$$t_{ee} = t_t + t_p + t_s + t_c \quad (1)$$

where t_t is the transmission time between the device and the gateway, also called Time on Air (ToA), t_p is the propagation time between the device and the gateway, t_s is the delay of



(a)



(b)

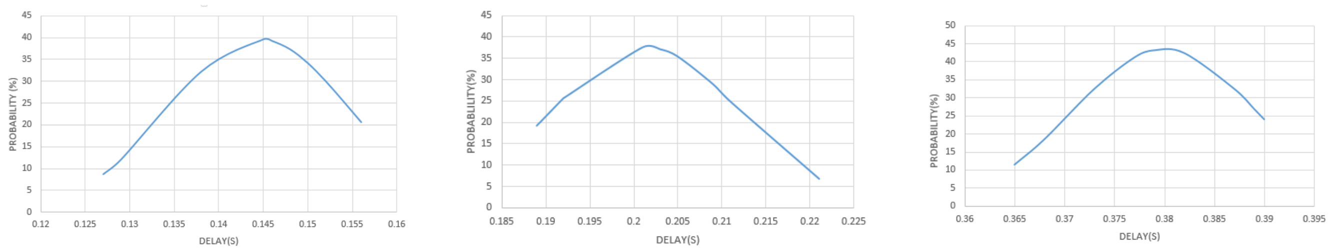
Figure 12: Density functions of consumed energy measured during the in-the-lab test while waiting (a) and transmitting (b)

the satellite link, and t_c is the delay within the Internet until the packets reach the cloud platform.
We performed some tests introducing 3 different delay values for t_s: 10 ms, 70 ms, and 250 ms, in order to simulate the presence of a LEO, a MEO, and a GEO satellite, respectively. The obtained results in terms of t_{ee} density function, whose samples are computed looking at the packet timestamp added by the device when it sends each packet and the time instant when the TTN receives it, are reported in Figure 14.

Due to the low data rates of the LoRa protocol, in most cases t_t has the greatest value among the Eq. (1) terms. It is typically ranged between about 50 and 1,500 ms depending on the SF and the packet size. In our case, in both on-the-field and in-the-lab tests, the used SF is 7 as mentioned before. For this reason, $t_t = 51.5$ ms (as also shown in the sixth column in Figure 13) and t_p can be considered negligible.
The gateway keeps forwarding data in all cases, which proves the robustness and tolerance of the system in case of the satellite presence in the path between the gateway and the cloud platform in terms of delay.

6. Conclusion and Future Work

The integration of UAVs and satellite in the IoT field is presented in this paper. The idea of employing a flying gateway based on the LoRaWAN IoT solution equipped on-board a drone has been realized and tested in practice.



(a) (b) (c)

Figure 14: Density functions of the end-to-end delivery time with $t_s = 10$ ms (a), $t_s = 70$ ms (b), $t_s = 250$ ms (c)

The aim of this flying gateway is to extend the current limited coverage of the commercial IoT solutions and to integrate them with the terrestrial network. The exploitation of the satellite connectivity has been considered especially to overcome the lack of other communication infrastructure in certain locations, such as rural and remote areas, and looking for the possible integration of these network foreseen in the 5G framework. Our system was tested in two environments: lab environment and outside environment. The results of both tests are presented and explained showing the feasibility of our approach.
As future work, we aim to increase the number of sensors to have a wider testbed able to more realistically emulate a smart agriculture scenario. We will better simulate/emulate the satellite link through the introduction of proper available and more sophisticated tools, such as OpenSAND. OpenSAND tool allows to emulate different types of satellites, with respect to the IoT case study LEO satellite will be considered. Moreover, we aim to improve the gateway capability towards a multi-protocol gateway approach, i.e. to have an unique UAV able to act as a gateway of different IoT communication solutions at the same time.

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