The PLATINO Experience: A LoRa-based Network of Energy-Harvesting Devices for Smart Farming

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***Abstract*—Framed within the PLATINO research project we have prototyped an energy-harvesting device specifically designed for supporting a set of smart farming applications. To this purpose, our prototype is equipped, among other components, with several sensors for environmental and energy conditions monitoring and a LoRa communication module to enable a Low-Power Wide Area Network. The physical network will be composed of dozens of PLATINO devices acting as end-nodes and of a drone with limited time of flight acting as a mobile gateway, which will receive the data temporally stored on the end-devices. This paper analyzes the set of constraints imposed by the European LoRa regulations and by the drone itself to design an efficient communication protocol between the drone and the end-devices.**

***Index Terms*—Smart Farming, Testbed, LoRa technology.**

I. Introduction

Smart Farming [1] is the application of the Information and Communication Technologies (ICT) for optimizing the agricultural production. Differently to the Precision Agriculture concept, which is more focused on the optimization process to compute and apply the precise amount of *inputs* (e.g. water, fertilizers, pesticides) at the correct moment of time to produce the output maximization (e.g. quantity and quality), the Smart Farming is focused on the data collection process itself, on the data processing and on its interpretation, to generate knowledge that can be later applied in a smart way.

Although sensors have been used in agriculture for many years for the monitoring of different parameters of interest (e.g. meteorological, environment, soil and plant), modern ICT combine sensing capabilities [2] with more sophisticated data processing, geo-positioning, and wireless communication. In this sense, the PLATINO research project pursues the realization of the Smart Farming concept by means of the fusing and processing of heterogeneous data collected through a set of cutting-edge hyperspectral and photonic sensors that are embedded into end-devices distributed on the target crop field. These devices will send the acquired data towards a drone that acts as a mobile gateway, which will be available only for a short time at specific moments of the day, when the communication between devices and drone will take place. After the flight, the drone comes back to its original location and the data will be permanently stored into a server for further processing and analysis, with the purpose of generating maps with relevant information for the farmers.

To meet the requirements of the PLATINO project we have built an end-device prototype for experimentation targeted to support the data collection of multiple variables of interest under different energy requirements and meteorological conditions. The end-device includes a solar panel as energy-harvester and a LoRa communication module to enable the data transmission towards the drone through a Low-Power Wide Area Network (LP-WAN). Section II reviews and compares some of these LP-WAN technologies. This paper describes three major contributions: 1) the PLATINO end-device that is used for the data collection (Section III); 2) the design of a LoRa-based protocol between the end-devices and the gateway to transmit the data collected (Section IV); and 3) a quantitative analysis of the protocol parameters to meet the LoRa constraints (Section V). In Section VI we draw the main conclusions and make suggestions for further research.

II. LP-WAN Technologies Overview

LP-WAN [3] are characterized by a long range communication, a low data rate and a low energy consumption that are demanded by many applications intended to the outdoor monitoring. There exist four technologies currently considered in the IETF LP-WAN Working Group: LoRa/LoRaWAN, NB-IoT, SigFox, and Wi-SUN FAN. This section describes them briefly, making special emphasis in LoRa/LoRaWAN. The reader can consult the work [4] for a further comparison between LoRa/LoRaWAN, SigFox and NB-IoT.

LoRa (Long Range communication) [5] is one of the most popular enabling technologies for LP-WAN. While LoRa standardizes a set of parameters at the physical layer, the LoRaWAN specification [6] describes the media access control protocol and the network protocol (second and third layer of the OSI model, respectively) on top of the LoRa physical layer. In particular, LoRa specifies: **1) Modulation**: LoRa uses Chirp Spread Spectrum (CSS), a spread spectrum technique where the signal is modulated by chirp pulses to encode information, hence improving resilience and robustness against channel noise, Doppler effect and multipath fading; **2) Frequency bands**: LoRa operates in the unlicensed ISM frequency bands of 863-870 MHz in Europe, 902-928 MHz in United States, 915-928 MHz in Australia, and 779-787 MHz and 470-510 MHz in China; **3) Bandwidth**: depending on the frequency bands used, LoRa divides the band in different channels for uplink (messages from the end-device to an application running on a server) and downlink (a message from the application to the end-device). For example, in Europe LoRa uses three channels of either 125 KHz, 250 KHz or 500 KHz and in US it uses 8 sub-bands that result in 8x125 kHz uplink channels, 1x500 kHz uplink channel and 1x500 kHz downlink channel. The longer bandwidth the longer data rates and the lower transmission times; **4) Spreading factor (SF)** is the number of symbols sent per bit, since 1 bit is encoded as multiple chirps. LoRa defines SFs between 7 and 12, where the number of chirps per symbol is computed as 2^{SF}, therefore, the higher SF the slower transmission time (also known as airtime) and the longer the communication range; **5) Coding Rate (CR)** is the error correction coding, where higher values involve more overhead and higher reliability. The available rates are 4/5, 4/6, 4/7 and 4/8; **6) Transmission power** ranges between 5 and 23 dBm, where higher powers increase the energy consumption; **7) Data Transmission Rate** is the amount of data transmitted by unit of time (bps). Depending on the SF and bandwidth, the data rate ranges approximately between 0.3 and 27 Kbps; and **8) Packet format**: A LoRa packet is composed of three elements: a preamble (8 symbols by default), an optional header (13-23 bytes in LoRaWAN), a variable-length payload and a CRC (1 byte).

LoRaWAN enables end-devices may communicate with Internet-connected applications over long-range wireless connections providing also addressing and security. The LoRaWAN specification identifies three classes of devices: 1) Class A is the most basic class implemented by all end-devices, it supports bi-directional communication where each uplink transmission (based on ALOHA protocol) is followed by two short downlink receive windows; 2) Class B implements also bi-directional communication and uses additional receive windows at scheduled times; and 3) Class C keeps receive windows open except when they are transmitting.

A typical architecture for a LoRaWAN-based network is a star-of-starts topology: end-devices broadcast messages to multiple gateways by using 1 single hop and, in turn, gateways forward these (uplink) messages to a network server through an IP-based network, e.g. WiFi or Ethernet. The network server is then intended to filter duplicate packets, perform security checks and network management, and route the LoRa packets towards the target application. Additionally, the application could generate a downlink message and send it to an only end-device through the network server and a single gateway. Note that every gateway may cover several kilometers and serve up to thousands of end-devices; these parameters, together with the restriction of the duty cycle (see Section II-A), should be considered to determine if the technology is adequate for each particular case use. LoRaWAN distinguishes between six different MAC message types (join request, join accept, unconfirmed data up/down, and confirmed data up/down) and defines a set of commands for network administration.

SigFox [7] is a LP-WAN technology designed to enable billion of objects broadcasting only a few bytes per day without the need of establishing and maintaining connections. Currently, it is present in 60 countries and regions, 5 million square kilometers and 1 billion people. SigFox uses the Ultra Narrow Band modulation and operates in the 200 kHz of the ISM band to exchange radio messages over the air. SigFox achieves a data rate ranging between 100 to 600 bps, with a maximum packet payload of 12 bytes (uplink) and 8 bytes (downlink) and a number of packets per device that cannot exceed 140 packets/day (uplink) and 4 packets/day (downlink). The model however fits well with many IoT applications that need transmit sporadically small pieces of data, reducing thus their power consumptions (lifetimes in the order of years). As in LoRa, SigFox end-devices cannot operate with duty cycles larger than 1%. NB-IoT [8] is developed and standardized by 3GPP to enable a cellular-based solution for IoT. NB-IoT uses the narrow band of 180 kHz both for uplink and downlink and supports data rates of up to 60 Kbps (uplink) and 30 Kbps (downlink) and packet sizes of up to 1600 bytes, that are fragmented at the link layer into small pieces of 16 bits. NB-IoT uses licensed bands which means that end-devices could operate with duty cycles of up to 100% but, in turn, this supposes a higher price due to the license, deployment, and end-device costs. Wi-SUN FAN (Field Area Network) [9] is a wireless communication technology designed for Smart Utility Networks and characterized by wide coverage (2-3 kilometers), high bandwidth (up to 300 Kbps), and low-link latency (0.2 seconds), low-power consumption (2-8μ A), and high scalability ($5{\cdot}10^3$). Wi-SUN FAN is based on IEEE, IETF, and ANSI standards such as IEEE 802.15.4e/g for specifying and defining an IPv6 wireless mesh network on top of the TCP/UDP transport protocols providing robustness, reliability and long-term battery operation. Table I compares the four technologies across a set of factors.

A. *LoRa Limitations*

In spite of LoRa raises as one of the most preferred technologies for long range communication there exist some limitations which could make it not adequate for some applications. The duty cycle, i.e. the fraction of time during which a device using unlicensed bands can occupy a channel, is regulated in Europe by ETSI EN300.220 standard, which defines a maximum duty cycle of 1% for all sub-bands in the spectrum. This means that a LoRa device can transmit up to 36 seconds per hour, which is a key constraint for IoT applications aimed at transmitting real-time data at high frequencies, or the ones that transmit multimedia data flows. Such a restriction impacts both on the length of the messages to transmit (payload) and on the time among messages. In practice, an application using LoRa should be programmed to keep itself within these limits, which can be done by calculating in advance the maximum sampling period, the message payload, the airtime for that message and how much time an end-device should wait to transmit the next message. Note that, in order to maintain the size of the payload as minimum as possible, an application could implement different techniques such as transmitting only aggregated data (avg, max, min), data compression, and avoiding transmitting non-binary data (e.g. JSON, XML). Up to date the LoRa modules support only half-duplex communication, which means a LoRa device cannot transmit and receive simultaneously.

TABLE I

COMPARISON OF LP-WAN TECHNOLOGIES ACROSS DIFFERENT CHARACTERISTICS. **LEGEND: UP:** UPLINK. **DOWN:** DOWNLINK. **NA:** NOT AVAILABLE.[1]**: LOS:** LINE OF SIGHT (EXTENDED VIA MULTI-HOP NETWORKING).

Factor	**SigFox**	**NB-IoT**	**LoRa/LoRaWAN**	**Wi-SUN**
Coverage (Km)	10 (urban), 40 (rural)	1 (urban), 10 (rural)	5 (urban), 20 (rural)	2-3 LoS[1]
Data rate (Kbps)	0.1	200	0.3-27	50-300
Max. Payload (bytes)	12 (UP), 4 (DOWN)	1600	243	IP packet payload
Max. messages/day	140 (UP), 8 (DOWN)	Unlimited	Unlimited	Unlimited
Scalability	10^6/gateway	$55 \cdot 10^3$/cell	10^4/gateway	$5 \cdot 10^3$
Device/Spectrum cost	<2€/Free	>20€/>500M€/MHz	3-5€/Free	NA/Free

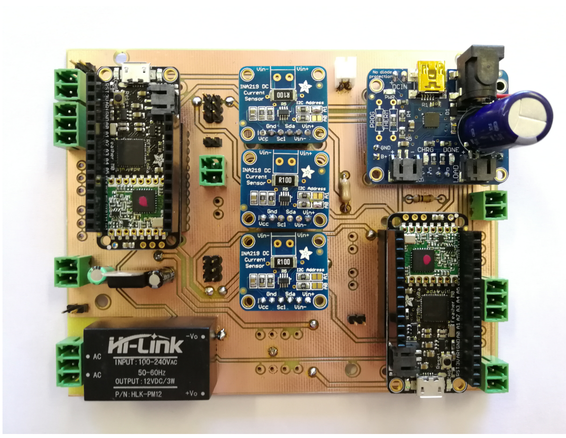

Fig. 1. The PLATINO testbed (taken from [10]).

III. THE PLATINO TESTBED

Based on the project needs the ARCO group has designed the PLATINO testbed (see Figure 1), which provides a flexible and modular tool for supporting the uninterrupted execution of applications by means of an energy harvester, which let the battery level grows depending on the application consumption that is being executed and the weather conditions. The testbed is composed of two independent microsystems that provide specialized functions using different technologies: the Smart Farming Device includes a set of sensors to implement a set of outdoor monitoring applications and the Data Logger, that independently records energy-related parameters about the battery and the harvesting subsystem. Both microsystems have separate power suppliers and are connected through a serial interface. A complete description can be found in [10].

A. Smart Farming Device

The Smart Farming device is based on an Adafruit Feather M0 [11] microcontroller with an RFM95 LoRa radio and capabilities of energy-harvesting and sensing. We have selected LoRa as network technology due to its wide coverage, low-cost and power efficiency and, according to Table I, because it permits unlimited number of messages per day with longer data rates as compared against its main competitor SigFox.

The choice of including an energy harvesting system obeys to the need of increasing the device autonomy by enlarging its lifetime. The energy harvester is currently based on a 2 Watts photovoltaic solar panel (PV) [12], a solar charger to operate the power conversion and an energy storage based on a lithium rechargeable battery, which has a capacity of 2000 mAh with a nominal voltage of 3.7 V, and the output ranges from 4.2 V (when fully charged) to 3.3 V (when fully discharged). The PV provides a nominal current of 340 mA with an output voltage of 6.5 V. The solar charger can provide the output power directly to the load output, where the Smart Farming device is connected, if the harvested energy is sufficient to maintain the operation of the device and the battery is completely charged; otherwise, if the battery is not completely charged and the panel production is not sufficient, the current from the PV is used to charge it and the current is supplied from the battery. The energy harvesting system could be extended to include other harvesting sources (i.e. wind turbines).

The sensing subsystem includes 20 general purpose I/O pins, with up to 10 analog input pins, 8 Pulse-Width Modulation outputs and UART, SPI and I2C communication interfaces. The PLATINO testbed includes also the SHT10 Mesh-Protected and Weather-Proof sensor [13] to measure the environment temperature between -40 and 123.8 °C, and a relative humidity between 0 and 100%.

B. Data Logger Device

The Data Logger (DL) device is based also on another Adafruit Feather M0/RFM95 LoRa radio, with additional capabilities of storing through a micro SD card, real-time clock (RTC), visualization of the current system state through an OLED monochrome display and energy conditions monitoring. For this last purpose, three INA219 [14] sensors are used to measure the battery, Smart Farming device, and PV currents and voltages. This module supports the I2C interface, operating only as a slave device and it features up to 16 programmable addresses. The default register configuration is used, enabling to measure a range of ±3.2 A, with a resolution of ±0.8 mA. The DL estimates the solar irradiance by a latched mini relay that measures the short-circuit current of the panel. Additionally, the DL uses an anenometer [15] to measure the wind speed with an analog output in the range 0.4∼2V and wind speed values from 0.5 to 50 m/s.

IV. System Model

We consider a LoRa-based network with n PLATINO end-devices $\mathcal{P} = \{p_1, p_2, \ldots, p_n\}$ geographically distributed at specific locations over a crop field of area A and one only gateway G that is operated by a drone which overflights the terrain two times per day, at the first hour in the morning t_i^1 and two hours after the noon t_i^2 ($t_i^1, t_i^2 \in [0, 23]$ hours of day i). The duration of the drone flight is limited to T_{flight}, during which every p_k transmits to G in 1 single hop the data previously collected and temporally stored into their memory cards. Specifically at t_i^1, p_k ($k \in [1, n]$) transmits the data collected within the interval $l_1 = [t_{i-1}^2, t_i^1]$ and at t_2 the data collected within $l_2 = [t_i^1, t_i^2]$. We assume that n is lower than the maximum number of nodes per gateway and that the diagonal of A is lower than the LoRa line of sight (LoS).

The process of data collection includes the sampling at some frequency s_1 and s_2 of 7 sensors attached to each $p_k \in \mathcal{P}$: temperature ($^\circ C$), humidity (%), wind speed (m/s), Smart Farming node current (mA), short-circuit current of the panel (solar irradiance) (mA), battery current (mA) and battery voltage (V). By assuming that each sample occupies B bytes and that s_1 and s_2 represent the sampling frequencies in each interval expressed as a number of samples per hour, the amount of data in bytes collected at the end of the first period l_1 is $D_1 = 7B \cdot s_1 \cdot (24 - t_{i-1}^2 + t_i^1)$, and at the end of the second period l_2 is $D_2 = 7B \cdot s_2 \cdot (t_i^2 - t_i^1)$. This means that, without taking into consideration additional data, D_1 and D_2 should be transmitted at the end of the intervals l_1 and l_2, respectively, by each p_k to the drone G during T_{flight}. There exist three constraints that apply here: **Constraint 1 (C1):** the payload in LoRa is limited to 51 bytes for low data rates (SF12) and up to about 222 bytes for best conditions (SF7); therefore, and regardless the SF used, if D_1 and D_2 exceeds that size we will need to fragment the data into smaller packets that should be consecutively transferred from p_k to G; **Constraint 2 (C2):** Let n_{packet} be the number of packets to be transferred from $p_k \in \mathcal{P}$ to G in each interval, the sum of the times of transmission of n_{packet} cannot exceed the maximum time of transmission given by a $DC = 1\%$, i.e. 36 seconds/hour. Furthermore, in order to keep these limits, after sending a packet an end-device should wait T_{wait} before sending the next packet; and **Constraint 3 (C3):** T_{flight} is also limited, which means that the transmission data process from each p_k and the reception of these data by G should be accommodated in a maximum window size of T_{flight}.

Problem Statement: Given a set of configuration parameters for the LoRa communication modules employed by p_k and G, specifically, payload, SF, bandwidth, and coding rate, the problem to solve consists in computing the sampling frequencies s_1 and s_2 to be used during the interval l_1 and l_2 to get maximizing the number of samples that will be transferred for each p_k while the constraints **C1**, **C2** and **C3** hold.

A. Determination of the Sampling Frequencies

Let us to consider the transmission of a LoRa packet with a certain payload PL on a LoRa communication module configured with a certain SF and bandwidth (BW). According to [16], the transmission time of that packet is:

$$T_{packet} = T_{preamble} + T_{payload} \quad (1)$$

$T_{preamble}$ and $T_{payload}$ correspond, respectively, to the times to send the preamble and the payload, specifically:

$$T_{preamble} = T_{sym} \cdot (N_{symPreamble} + 4.25) \quad (2)$$

$$T_{payload} = T_{sym} \cdot N_{symPayload} \quad (3)$$

where $T_{sym} = \frac{2^{SF}}{BW}$ is the time to send a single symbol, and $N_{symPreamble}$ and $N_{symPayload}$ are the number of symbols in the preamble and payload, respectively, with:

$$N_{symPayload} = 8 + \max\left(\left\lceil \left(\frac{8PL - 4SF + 28 + 16 - 20H}{4(SF - 2DE)}\right)(CR + 4)\right\rceil, 0\right) \quad (4)$$

with $H = 0$ if the header is present (otherwise, $H = 1$) and $DE = 1$ if the low data rate optimization is enabled (otherwise, $DE = 0$).

The constraints **C2** and **C3** stated before impact on the number of packets to be transferred. Given the $DC = 1\%$ and a certain T_{flight} (in minutes) we define the maximum time of transmission as $T_{airtime} = \min\{0.6, T_{flight}\}$. The maximum number of packets n_{packet} transferred during $T_{airtime}$ for packets of duration T_{packet} ms is:

$$n_{packet} = \left\lfloor \frac{T_{airtime} \cdot 60 \cdot 10^3}{T_{packet}} \right\rfloor \quad (5)$$

An end-device, therefore, cannot transmit the rest of the time in an hour, i.e. $60 - T_{airtime}$. Subsequently, the time to wait between packets, namely T_{wait} (also in minutes) is:

$$T_{wait} = \frac{60 - T_{airtime}}{n_{packet}} \quad (6)$$

Since we want to transfer n_{packet} during $T_{airtime}$ it follows that the number of samples collected during the periods l_1 and l_2 should be n_{packet}, and the number of samples/hour is computed as $s_1 = \frac{n_{packet}}{l_1}$ and $s_2 = \frac{n_{packet}}{l_2}$, respectively.

B. Drone-Device Network Protocol

The communication strategy between the drone G and p_k follows an hybrid approach between TDMA and CSMA. In each end-device two timers will be configured to expire at times t_1 and t_2. Under each timeout, G and p_k will proceed to execute the data interchange defined in Protocol 1.

V. Evaluation

We analytically compute the sampling frequencies s_1 and s_2 that could be used in the scenario described for different T_{flight} and LoRa configurations. We respect the constraint given by the European regulation that limits the duty cycle and assume the next parameters for all end-devices: one channel of bandwidth BW=125kHz within the European frequency band 868.0MHz, a spreading factor $SF \in [7, 12]$, coding rate $4/5$, and a size of payload PL ranging between 10 and 150 bytes. To reduce the size of the messages we eliminate the header from the LoRa packets.

Protocol 1 $G - p_k$ Communication Protocol

Inputs. Let n_{packet} be the number of data packets to be transferred from each p_k to G. Let T_{wait} the waiting time before sending the next data packet.

Goal. G receives n_{packet} from each $p_k \in \mathcal{P}$

The protocol:

1) **Initialization.** j = 1
2) **Synchronization.**
   a) $G \rightarrow p_k$: m1 = (DevUID-G) $\forall p_k \in \mathcal{P}$
   b) $p_k \rightarrow G$: m2 = (DevUID-p_k) $\forall p_k \in \mathcal{P}$ after validating DevUID-G and goes to **step 3**
   c) G validates DevUID-p_k and goes to **step 3**
3) **Data Transmission.**
   a) G switches the LoRa module to reception mode
   b) $p_k \rightarrow G$: m3 = $(ID_j, Temp_j, Hum_j, Wind_j, PVCurrent_j, SFCurrent_j, BattCurrent_j, BattVolt_j) \forall p_k \in \mathcal{P}$;
   c) p_k switches the LoRa module on reception mode and waits T_{wait}
   d) $G \leftarrow p_k$: m3, saves m3 after validation; otherwise $G \rightarrow p_k$: m4 = (DevUID-p_k,ID_j) where ID_j is the lost packet
   e) **if** $j \leq n_{packet}$: $j = j + 1$, G goes to **step 3.a** and p_k goes to **step 3.b**; **else:** end transmission.

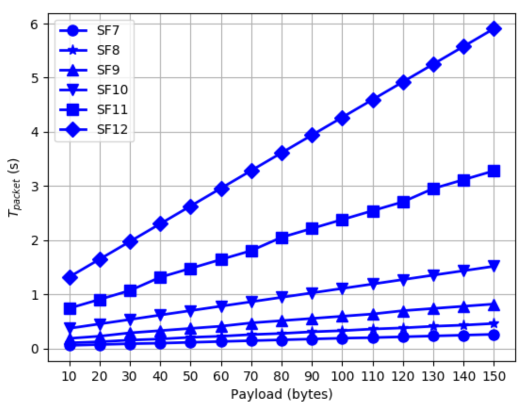

Fig. 2. T_{packet} for a LoRa packet with different payloads and SFs.

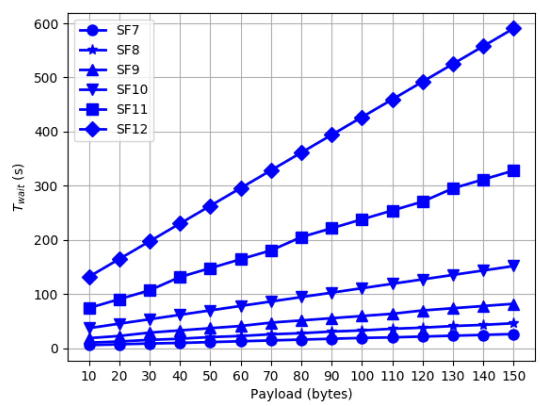

Fig. 3. Time to wait before sending the next packet (T_{wait}).

Figure 2 shows the transmission times for packets with different PLs and SFs. As observed, the larger the SF the longer transmission time (and longer communication range). An $SF\ i$ allows to send 2 times more bytes than an $SF\ i+1$ in the same time or, alternatively, allows to reduce the time approximately to the half for a same PL. The SF should be carefully chosen as it impacts on the transmission time. According to [17], large SFs are used more often than small SFs. An end-device that requires T_{packet} to transmit a packet should wait T_{wait} before transmitting the subsequent packet, which basically depends on the DC that is being used. Figure 3 shows the times to wait for packets with different PLs and SFs with a $DC = 1\%$. As observed, T_{wait} increases with the PL and SF, since a larger PL and SF involve a larger T_{packet}, which means that we will send less packets and wait a longer timer, because the time of no transmission has to be distributed among a small number of packets.

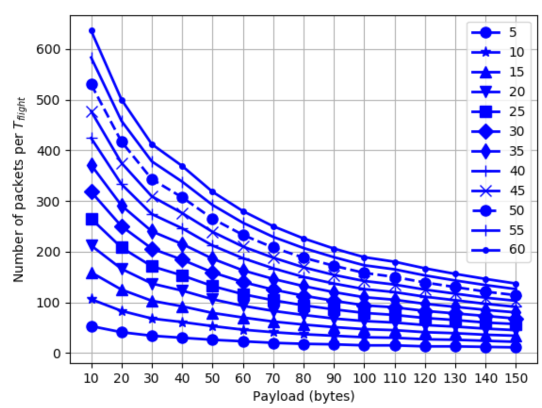

Fig. 4. No. of packets transferred during $T_{flight} = [5, 60]$.

We introduce now the constraint **C3** as a $T_{flight} \in [5, 60]$ minutes. Note that in this way, the transmission time could be still more limited since all activities of communication should happen within of that window time. The number of packets

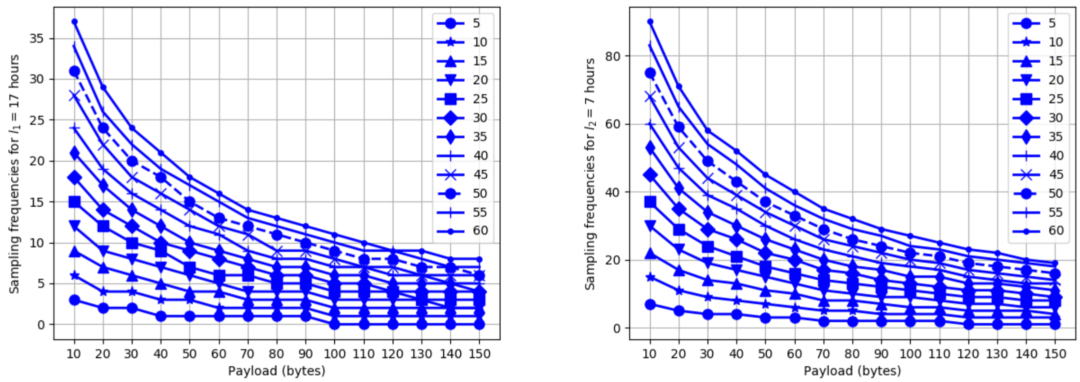

Fig. 5. Sampling frequencies to be used in the interval $l_1 = 17$ (on the left) and $l_2 = 7$ (on the right) hours.

with different PLs that can be transferred during T_{flight} for a specific $SF = 7$ is shown in Figure 4, where n_{packet} decreases when the PL increases, since we can transport data with a longer payload, and when the T_{flight} decreases, since the transmission window size is thus reduced. Note that we selected a $SF = 7$, which represents the best conditions. Since n_{packet} coincides with the number of samples to take during the entire periods l_1 and l_2, the sampling frequencies s_1 and s_2 are computed by dividing the number of packets between the number of hours in the interval l_1 and l_2, respectively. Figure 5 shows the values of s_1 (on the left) and s_2 (on the right) expressed in number of samples per hour with $l_1 = 17$ and $l_2 = 7$ hours for different PLs and T_{flight} given a $SF = 7$. s_1 and s_2 decrease when PL increases, since the number of samples, or equivalently, the number of packets to transfer will be also smaller; the number of samples is also affected by T_{flight}: the longer T_{flight} the higher sampling frequency.

VI. CONCLUSIONS

This paper describes a smart farming use case where the sensing devices pose challenges of energy-harvesting and long-range wireless communication. We have prototyped a low-cost modular testbed that faces these challenges by using a solar panel to maintain the prolonged execution of smart farming applications and a LoRa radio to enable a LP-WAN in absence of any network infrastructure. We investigate how LoRa limitations affect the design of a communication protocol between those end-devices and a gateway and we provide a quantitative analysis that has enabled to determine in advance some network and protocol parameters (e.g. packet times, wait times, and sampling frequencies). In line with the PLATINO project, the next step will consist in conducting a real deployment of end-devices on the crop field to assess not only the protocol performance (in terms of latencies, collisions, and data rates) but also the ability of the end-device to execute applications for long periods of times.

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