Agricultural LoRA sensor network applied to soil moisture monitoring for fertigation-based production.

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List of acronyms:

ABP: Activation by Personalization

AppEUI: Application Extended Unique Identifier

AppKey: Application Key

AppSKey: Application Session Key

BW: Bandwidth

CR: Coding Rate

CRC: Check Redundancy Cycle

DevAddr: Device Address

DevEUI: Device Extended Unique Identifier

HTTP: HyperText Transfer Protocol

IoT: Internet of Things

LoRa: Long Range

LoRaWAN: Long Rang Wide Area Network

LPWAN: Low Power Wide Area Network

MIC: Message Integrity Control

NwkSKey: Network Session Key

OTAA: Over the Air Activation

SF: Spreading Factor

SNR: Signal to Noise Ratio

TTN: The Things Network

Abstract

The global water crisis is one of the serious threats that human being is facing and especially farmers due to a variety of environment issues. This growing trend of water scarcity led to the existence of the efficiency of irrigation systems for agricultural proposes using electronic sensors and performance systems to precise the amount of water for the growth of plants. However, currently, some automation attempts led to a sub-optimal solution as they do not take into account the vegetative development state of the plants and the small differences in environmental conditions present inside greenhouses. In this project, the work is based on developping a monitoring system based on measurement nodes for real-time monitoring temperature, and humidity. Open-source hardware and sensors was use to create the measurement nodes using LoRa WAN a wireless sensor network. The aim of this work is to create a network of sensors inside a greenhouse in order to obtain regularly updated information. The data is going to be useful since is easy to utilize by the farmers directly from a platform. Measurement node, communicating in real-time through LoRa, will transmit data to the gateway which will then be displayed on a dashboard.

Keywords: wireless sensor networks, IOT, LoRa, sigfox, Wi-Fi Bluetooth, nodes gateway.

Introduction

The classic internet is a global system of interconnected computer networks which carries a vast range of information resources and services in which HTTP (Hypertext Transfer Protocol) is the first protocol used to transfer hypertext data, from server to the end customer. The classic internet is thus based on the internet of data.

On the other hand, the internet of things (IoT), is a new tool for connectivity and mobility, that is to transform business and is helpful in daily life to connect objects. Nowadays, common objects become active and intelligent, integrating seamlessly into a global network and can produce and exchange useful data without the intervention of humans. It's a network of networks that allows us to identify and communicate digitally with the physical and virtual world.

In the near future, the IoT will cover a wide range of applications in our daily life. The world is experiencing a huge increase of intelligent objects, that has led cloud service companies to make platforms known as the Internet of things platforms (IoT platform), which contain services, statistics, libraries, analyses that facilitate communication as well as accelerate and reduce the cost of product development of IoT applications.

Chapter 1 Work overview

1.1 Introduction

Agriculture has always been one of the main activities of humanity which is essential for our existence and growth. However, in today's world, water scarcity started posing a challenge for the indiscriminate use of water in irrigation systems. Indeed, a greater portion of the water supply consumed worldwide is used in agriculture and in an increasing rate with the ever-developing population and production methods. Thankfully, the same technological development can also offer the solutions to tackle the emerging challenges.

One of these new solutions is the emerging Internet of Things (IoT) field which is a new tool for connectivity and mobility that transforms business and the daily life due to connected objects. Nowadays, common objects become active and intelligent, integrating seamlessly into a global network, and can produce and exchange useful data without the intervention of humans. This tool, applied to the agricultural field specifically on the issue of water preservation, can offer new pathways.

Another important development was the introduction of the fertigation crop growing method which focuses on delivering precise amounts of nutrients to the plants in a way that optimizes water and overall nutrient consumption.

1.2 Problem description

The growing trend of water scarcity has led to an increasing pressure to increase the efficiency of irrigation systems for agricultural purposes. In order to implement an efficient solution for irrigation system regulation, there is need to set in place efficient data gathering systems that will drive decision-making. Indeed, without a proper sensory system, plants will have to be irrigated according to a schedule set by the farmer which does not take into account the specific environmental conditions and vegetative state. These problems can be circumvented by equipping each growth platform with a measuring node responsible for aggregating and transmitting information on the humidity level of the substrate and the temperature in the immediate vicinity. This method aims to minimize the amount of water used in the fertigation process through optimal nutrition control based on the current water status of the plant. That is, the irrigation scale will be defined based on the actual need of the plants and not only based on empirical rules.

1.3 Main objectives

This work intends to carry out a wireless network of sensors for use in precision irrigation. The measurement nodes will be distributed along with the production platforms and will monitor, among other variables, the moisture content in the substrate.

The main objectives of this work are:

- Development of hardware and firmware for measurement nodes.
- Development of a back-end for data collection and analysis.

1.4 Thesis Organisation

The work is presented in 5 chapters.

Chapter 1 contains the description of the problem as well as the main objective to solve this problem.

Chapter 2 presents the state-of-the-art wireless sensor networks applied to agriculture presenting the different technologies used including their concepts and tools.

The long-range wireless communication and the comparison between each technology is presented in Chapter 3.

In Chapter 4 we present the practical implantation and each step for the development of the work as well as the hardware and firmware.

The general conclusion and the idea of the future work are carried out in Chapter 5.

Chapter 2 IoT and wireless sensor network in agriculture

2.1 Introduction

The internet of things, can be understood as a network of interconnected intelligent devices capable of communicating with each other, generating data related to the environment in which they operate. IoT is based on connected objects which are able to capture data and send it, via the Internet, where it will be analyzed and visualized on dedicated dashboards. Connected objects interact with their environment through sensors (temperature, speed, humidity, vibration…) and actuators. Although the idea of IoT is not new, its adoption has increased in recent years, mainly due to the development of technologies that support it. Improvements in connectivity with the Internet and between devices via a wireless connection, cloud computing, artificial intelligence, and big data help to build a network of devices capable of sharing data and information, as well as acting actively based on input. A connected object can communicate with the physical world without human intervention. It has different constraints such as memory, bandwidth, or consumption of energy and it has a capacity to receive and transmit data with software. [1]

There is no standard, unified definition of the Internet of Things. Some definitions emphasize the technical aspects of IoT, while others focus on uses and functionalities. IEEE defines IoT as a network of elements each equipped with sensors that are connected to the Internet [2]. CERP-IoT (Cluster of European Projects on the Internet of Things) defines the Internet of Things as: “a dynamic infrastructure of a global network which has self-configuration capabilities based on standards and interoperable communication protocols. In this network, physical and virtual objects have identities, physical attributes, virtual personalities, and intelligent interfaces, and they are integrated into the network in a transparent manner [3]. Others consider the IoT to be a network that allows, through standardized electronic systems, and wireless devices, to directly identify digital entities and physical objects and able to recover, store, transfer, and process, without discontinuity between the physical worlds and virtual, the attached data. The Internet of Things sits at the intersection of the fields of computing and electronic communications, where any communicating object can be interrogated, sends information, and interacts with its environment.

2.2 The importance of IOT

IoT becomes the first real evolution of the Internet with the ability to transform our way of life. The IoT has already endowed the internet of sensory capacities (temperature, pressure, vibration, luminosity, humidity, tension), which allows us to anticipate rather than just react. Additionally, the Internet now covers places that were previously inaccessible or hard to access [4].

The development and implementation of smart and IoT-based technologies have allowed for various possibilities in technological advancements for different aspects of life. The main goal of IoT technologies is to simplify processes in different fields, to ensure better efficiency of systems, and finally to improve life quality so it covers a wide range of applications and touches almost all areas that face such as:

- Early detection of infrastructural faults and better management of various networks such as water supply, electricity, and gas of smart cities as well as various other challenges. Sensors receive information and treat it to provide efficient and useful solutions, they can be used for the economy of water and to improve the management of parking lots, security, smart metering, smart energy systems, and urban traffic and reduce traffic jams and CO_2 emissions. In smart cities, many sensors are installed and connected with other devices over the internet which gives an alert to the users in case of any issues.
- Smart health: in the health sector, IoT will allow the deployment of personal networks for rehabilitation after a serious disease and the control of clinical signs, in particular for elderly people. Connected objects and smart medical devices have enormous potential, making it possible to monitor various vital and valuable human functions such as heart rate, skin temperature, movement monitoring, blood pressure, heart rate… This, will facilitate the remote monitoring of patients at home, and provide solutions for the autonomy of the disabled.

- Industry 4.0: Including IoT in industries improves the production process and ensures better communication between employee and machine. As can be seen in Figure 2, it allows full monitoring of products, the chain of production, all the way to the logistics and distribution chain by supervising the supply of the condition. This end-to-end traceability enables factories to improve the efficiency of their operations, optimize production and improve the safety of employees. Moreover, IoT improves the competition between companies in the market by providing efficient quality control with minimization of losses.

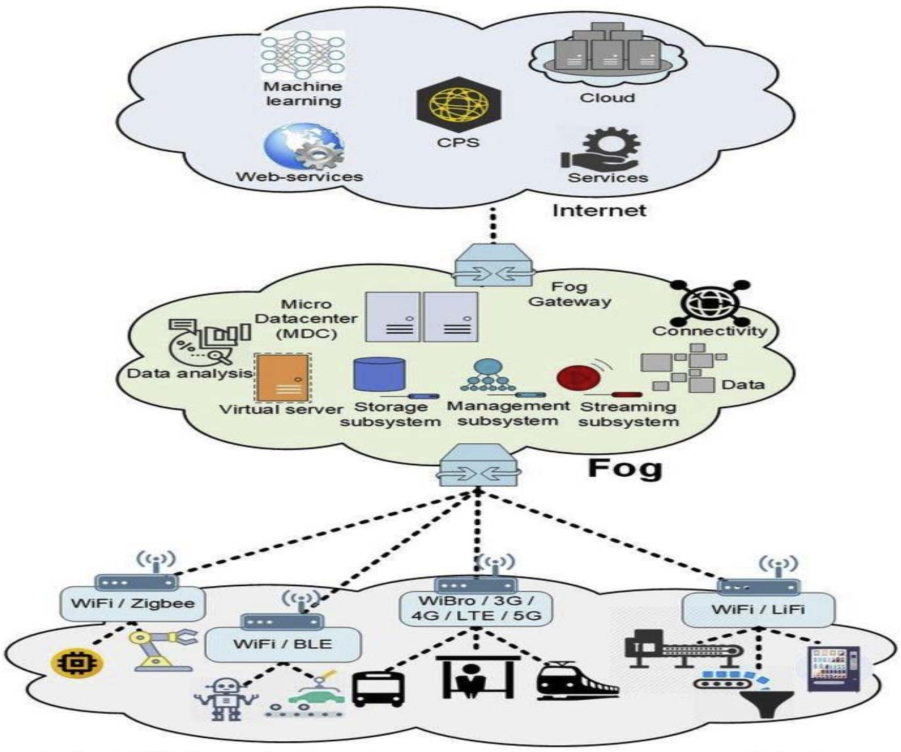

Figure 1 : General concept of IOT industrial application [5]

- Precision agriculture: The sustainability of agriculture is a key factor to overcome the potential lack of future food resources caused by different factors such as population growth and climate change, which may cause a reduction in the yields of crops. In recent years, agriculture is becoming more and more developed, and it's forced to modernize the methodology by taking advantage of the opportunities and the facilities provided by the Internet of Things. The implementation of IoT technologies in agriculture can help to secure sufficient food demands and increase the efficiency of agricultural production processes in general. For example, data about crops could be collected and used for yield monitoring and the detection of potential diseases. The soil monitoring system allows farmers to collect data about rainfalls temperature, humidity, and other metrics over time which can lead to water savings.

The wireless sensor network is present in different applications, especially in agriculture which makes it evaluated by employing information technologies to improve both quality and production. It is considered as a fundamental key to improving crop yields and minimizing the implication of farmers. Hence several ideas were applied in precision agriculture and this chapter presents the bibliographic revision of some projects put in application citing the communication protocols used [6].

3.2 State-of-the-art on WSN applied to agriculture

In [7] an article about Underground Wireless Data Transmission using 433-MHz LoRa for agriculture was published in 2019, Wireless sensor networks have been widely used in agriculture in a way to improve productivity through the provision of real-time sent data. These technologies are still not largely used due to the risk of damage of nodes in farms by machinery and extreme weather events. The solution exposed is to bury all sensors and communication components below the depth of cultivation, to form a wireless underground sensor network which has the potential to provide real-time data for agriculture without any damage for sensors. In this test, a 433 MHZ LoRa was tested for the evaluation of underground-to-underground in which the TX (received) and RX (transmitted) nodes were buried at the same depth at a range of transmission distances up to 50 m apart as shown in figure (3), and underground-to-approve ground communication where the TX node was buried at either 15 cm, 30 cm, or 50 cm depth, and the receiver node was fixed at 1.6 m above the ground surface, at a range of distances up to 200 m away from the TX node.

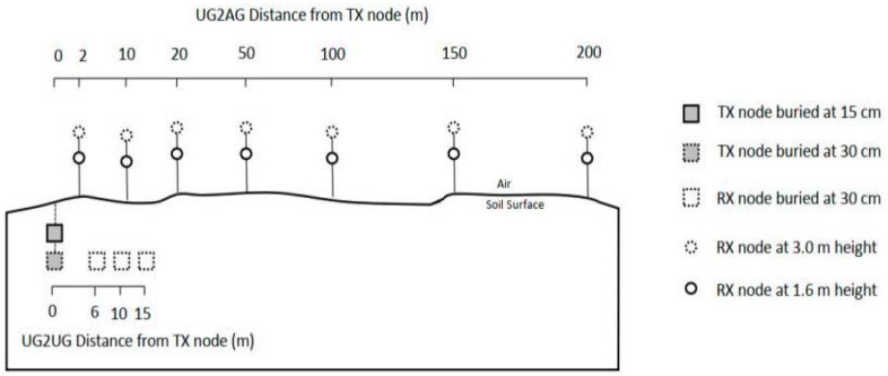

Figure 2 : Schematic of trial field layout [7]

In [8], Luis Manuel Fernandez–Ahumada et all published an article about a proposal for the design of monitoring and operating irrigation networks based on IoT, cloud computing and free hardware technologies. In the recent decades, the huge demand for food leads to a big consumption of water in farms which requires optimal water management, this demand face many facilities such as the large distances to electricity supply points and the lack of communication networks, but with the implementation of the wireless communication networks (Sigfox, LoRa WAN, and NBIoT) new perspective appeared for the automation of agriculture. The node is based on microcontroller ESP32-LoRa and internet connection through Sigfox network for optimizing the consumption of water used in irrigation.

The solution suggested is based on a gateway fixed next to the pumping station with some nodes distributed on the irrigated area as shown in this figure:

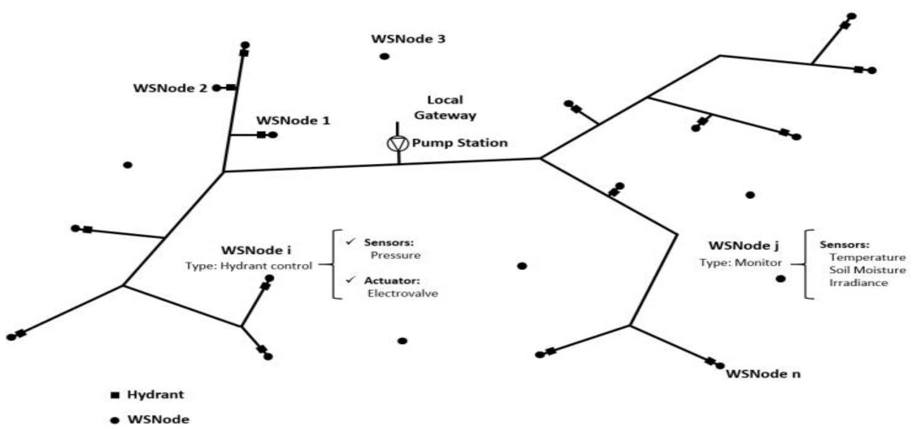

Figure 3: Node and local gateway distribution [8]

In [9], Danco Davcev et all, published an article about IoT agriculture irrigation system based on LoRaWAN: In the last decades, besides the implementation in the smart city applications and another social process, IoT has also found a place in the agricultural its usage is rapidly raised in this with great potential. In fact, an innovative and a highly scalable IoT agricultural system which is based on LoRaWAN network for low power consumption data transmission from the sensor nodes to the cloud services with a long-range data transmission capability to gives the opportunity to cover huge areas and to set up sensor nodes on great distance up to 15km. The prototype of the system is installed on a vineyard field to collect air temperature and humidity, as well as, the leaf wetness and soil moisture readings. The prototype is constructed of three collector nodes and one executor node which are positioned in a 1km radius from the base station. Based on the soil moisture and leaf wetness measurements, the analytics service takes a decision if the irrigation system needs to be turned on or not.

In [10], Olivier Debauche et all published an article about the Irrigation pivot-center connected based on LoRa modulation. Pivot-center is a widely used way of irrigation all over the world to fill the need of the crop watering, knowing by its lack of efficiency compared to the other systems, an automation system based on IoT and a LoRa module were proposed to improve the efficiency of water use. considerating, the different factors such as crop development, heterogeneity of soil, runoff, drainage, soil components, nutrients, and moisture content. This application has been tested in AIN SALAH located in the SAHARA desert region in Algeria which is characterized by a hot climate (47 up to50°C) in summer. The pivot center with a revolution time of 24h works with an angle of 15°every hour composed of 6 spans with a length of 308 m.

In [11], Alvaro Llaria et all published an article with a title “Geolocation and monitoring platform for extensive farming in mountain pastures using SIGFOX”. One interesting area for the IoT project is the monitoring of cattle, not only to improve the agriculture working conditions but also to control the behavior of the animals using Sigfox WSN. This technology is used in order to track animals in the field and to monitor their behavior in the summer based on the data issued from their movement taking into account the challenges in terms of energetic autonomy of embedded systems, wireless network coverage, and communication network architecture. SIGFOX technology is oriented to long-range transmission with low-rate and low-power consumption. By choosing this wireless communication solution, the large surface to be covered issues and the minimal energetic consumption of the geolocation devices problems have been solved. The transmission of the geolocation position given by the GPS is obtained once an hour, which is adequate with the SIGFOX network's data rate.

In [12], Nagpur, India, Ambarish G. Mohapatra et all published an article about Neural Network Pattern Classification and Weather Dependent Fuzzy Logic Model for Irrigation Control in WSN Based Precision Agriculture. The watering system plays a major activity in water and soil conservation, the future expectation of soil moisture content may push and ameliorate land watering system prerequisites. Some strategies were proposed to predict the hourly requirement of soil moisture content. The proposed system was utilized to solve a single problem that the generation of best irrigation suggestions for farmers. In this hybrid support system, the best optimization technique is used to predict the hourly variation of soil moisture, this predicted soil moisture content is utilized for generating appropriate notifications using a fuzzy logic-based weather model, the calculation was done hourly taking into consideration eleven distinctive soil and the parameters of the environment. A developed wireless sensor network (WSN) platform with a gateway is used to collect the agriculture data. This real-time monitoring and analysis of soil moisture content based on a low-cost wireless sensor network is located in the eastern region of India.

Chapter 4 LoRa based wireless communication

4.1 Introduction

The wireless sensor network (WSN) is a type of widely pervasive distributed system consisting of multiple unassisted devices called nodes, fixed in the yields having the ability to communicate through a wireless network, its function is to describe a monitored physical environmental condition, such as sound, vibration, pressure, temperature, lighting, humidity. WSN has rapidly evolved over the years enabling a spectrum of applications, and with the development of technologies. WSN has been paid great attention in several fields: industry, health care, disaster, medication, and especially agriculture. Although providing a layer amount of information to farmers, precision agriculture is a management strategy that employs information technology to improve both quality and production. This section presents the different wireless protocols that are compared to identify the most convenient technology in terms of power consumption and communication rate, where they have posed challenges in a current solution of IoT platforms in agriculture.

4.2 Technologies comparison

Electronic systems can be characterized by their consumption, their computing power, size, and price. In the specific case of on-board systems used in the IoT, we can assign the following weight to each of the characteristics:

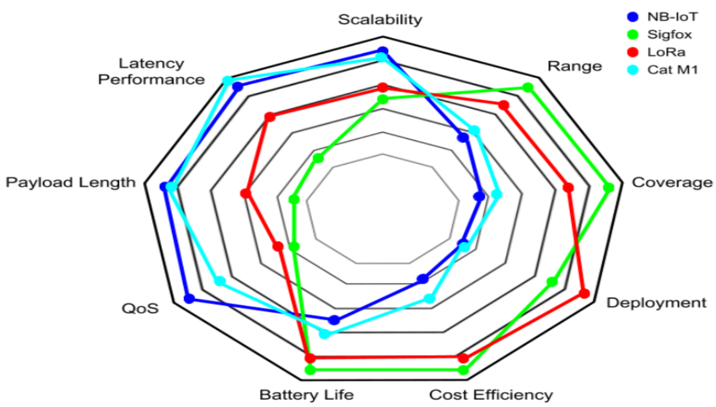

Figure 4: Characteristics of each LPWAN competitors [13]

In the IoT world, the following protocols can be classified according to their bandwidth and range as presented in Figure (10):

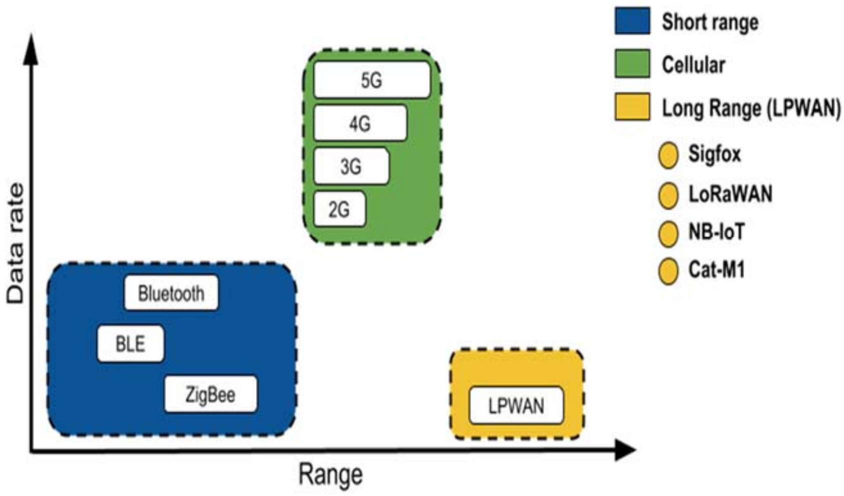

Figure 5: Data rate vs. range in communication network [14]

4.2.1 ZigBee:

ZigBee is a wireless sensor network technology that is extensively used in wireless control and monitoring application, because of small batteries reason of the low power, and mesh networking provides high reliability and layer Raye. This technology defended by ZigBee specification is intended to be simpler and less expensive than the other Wan as Bluetooth. ZigBee is addressed to the radiofrequency application that requires long battery life, secure network, and low data rate. Due to the low drafty cycle, ZigBee wireless protocol is conserved appropriately for agriculture such as irrigation supervision, water quality management, and fertilizer. The ZigBee protocol is composed of a physical layer that contains the radio frequency (RF) of the transceiver as well as it is a low-level control mechanism, and medium Access control agriculture monitoring systems [6].

4.2.2 Bluetooth

Bluetooth wireless technology is a short-range communication technology utilized to establish a communication link between portable devices with distance up to 10 meters while maintaining a high level of security. Due to its disponibility in most movable devices, Bluetooth was appropriated in multi-level agriculture; boil moisture, position, and temperature are monitored remotely using Bluetooth. Given its low energy consumption, large availability, and ease of use for formers; smartphones based on Bluetooth are employed in many agricultural applications, such as monitoring soil, migration controlling systems and the control of fertilizers and pesticides quantity. A fundamental Bluetooth strength is the capacity to simulate the transmission of data voice at the same time, to penetrate solid defects, it's omnidirectionality and the fact that it does not require line of sight positioning of connected devices [6].

It is primarily designed for low power consumption with a short-range, where the transmission changes depending on the Bluetooth devices in use from 1 to 100 meters. The devices are classified into three powered classes:

- Class 1: for a range of 100 meters with a maximum permitted power of 100 Mw (20dBm)
- Class 2: for a range of 10 meters with a maximum permitted of 2-5 Mw (4 dBm)
- Class 3: for a range of 1 meter with a maximum permitted power of 1 Mw (0 dBm)

4.2.3 SIGFOX:

Sigfox is a narrow wireless cellular network it's specifically considered for applications involving a limited number of field devices and requiring a long communication range. To compensate for such short ranges, the filed devices may be organized in a mesh network topology supporting multi-hop transmission. The allowed data transmission per day is 140 messages of 12 bytes are repeated over different frequency channels to increase the transmission. Sig fox was applied in the relocation and monitoring platform to help formers locate their cattle and enhance their production [6].

The LoRa wireless protocol covers a large communication area with low power consumption comparing to the other wireless communication technologies like shown in the table1, Therefore, it can be suitably deployed in vast agricultural fields:

Table 1: The different wireless communication technologies [6]

Standard	LoRa	Zigbee	BLE	WIFI
Frequency Band	868/915 MHz	868/915 MHz	2.4 GHz	2.4 GHz
Number of RF channels	10 in EU	1,10 and 16	GMSK	11
Spreading	CSS	DSS	FHSS	CCK
Communication range	≤5 KM	100 m	10m	100 m
Channel bandwidth	< 500 kHz	2 MHz	1 MHz	22 MHz
Application	Agriculture, smart grid, environment control	WPAN's, WSN and agriculture	WPAN's	WLANs
Power consumption	100 mW	369 mW	10mW	835 mW

4.3 LoRa and LoRa WAN

LoRa spread spectrum is a physical layer and a modulation technique to create the communication link, to send data. it is the acronym of Long Range, considered as the new ISM (Industrial, Scientific, and Medical) frequency band-based technologies and designed for low power, long-range operation. LoRa was developed by Semtech and is based on chirp spread spectrum (CSS) modulation. It presents a wireless technology where a sender can transmit and receive a data package over a long distance (up to 15 km). In addition, LoRa can be used with public, private, or hybrid networks to achieve a greater range than cellular networks and can easily integrate with existing networks and enables low-cost, battery-operated Internet of Things (IoT) applications [15].

The LoRa physical layer uses Chirp Spread Spectrum modulation, which is a technique of modulation that uses wideband linear frequency-modulated chirp pulses (frequency varying sinusoidal pluses) to encode information as shown in Figure 11, it represents the physical layer and has the same low-power characteristics as frequency-shift keying (FSK) modulation. [16]

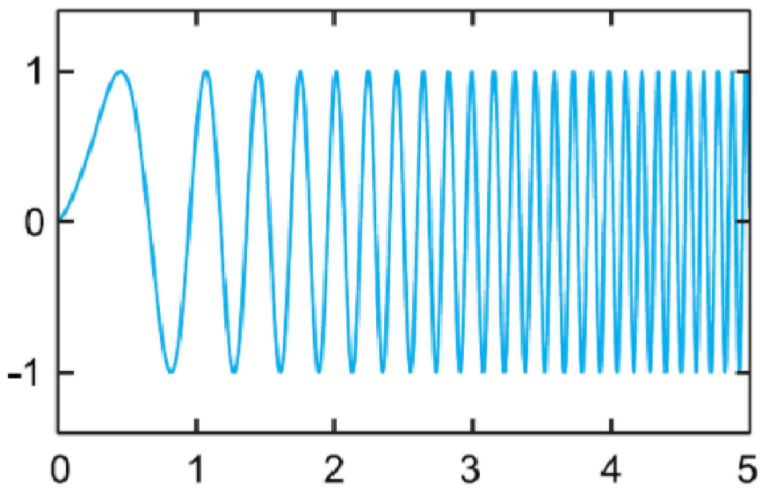

Figure 6: Chirp of LoRa modulation [17]

Based on the bandwidth and the Signal-to-noise ratio (SNR), a variable number of chips per bit named the spreading factor is chosen to spread the signal to make it more robust to noise. Thus, each bit is spread by a chipping factor, the number of the spreading factors are from 7 to 12 decides on how many chirps, the carrier of the data, are sent per second. A small spreading factor means more chirps sent per second which means high data rates and requires less over-the-air time. A large spreading factor implies less chips per second, which means a low data rate to encode per second and needs more over-the air time.

The shape of a chirp is shown in the figure below where the frequency of chirps is represented in term of time with a bandwidth of 125 kHz centered around a frequency of 868 kHz (channel).

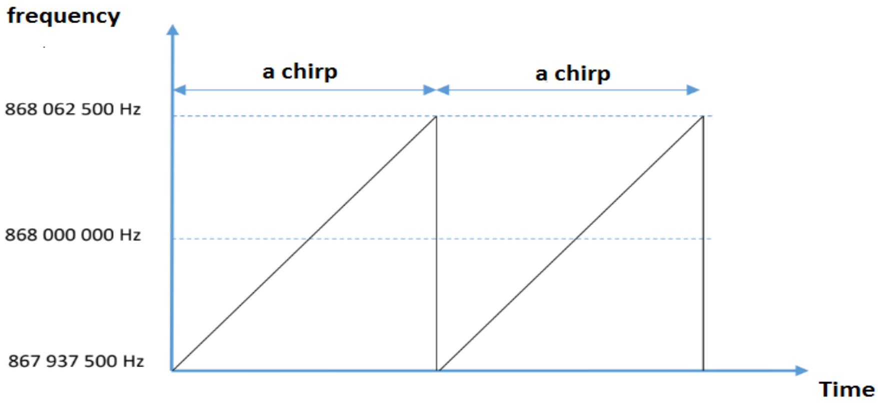

Figure 7: Shape of chirp

Each chirp (symbol) is a carrier of data, that each one represents a binary number that is received by a gateway and a server. The representation of chirps is shown in figure (27) with the same frequency channel (868mHz) and same bandwidth (125mHz), the first chirp sweeps from a low frequency to a high frequency. Additionally, in this example, every chirp is represented into 2 bits, hence 4 different chirps should be given as a result (00,01,10,11). In this case, since only 2 bits are represented, the spreading factor (SF) is 2. This is why the number of bits is always the origin of the spreading factor, hence in LoRa every chirp is represented by several bits:

Number of bits transmitted = spreading factor

Moreover, if the transmission uses a spreading factor of 10 (SF10), the chirp must be represented in 10 bits.

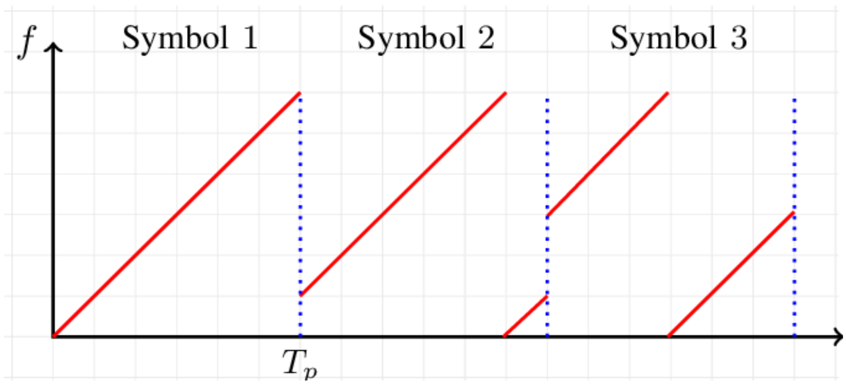

Figure 8: Symbols issue in LoRa modulation [18]

LoRa modulation is complex and the most robust to background noise, it uses two frequencies of frequency shifting key, and the sweeping between those two frequencies is shown in the figure below:

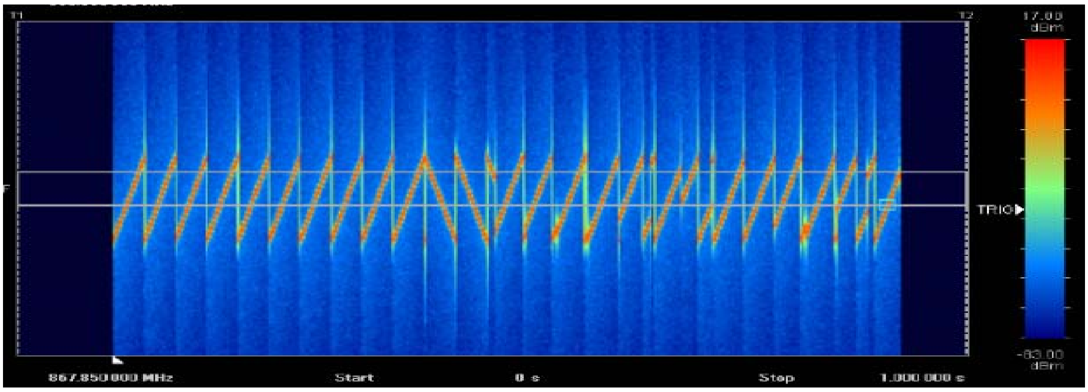

Figure 9: Sweeping between the two frequencies [19]

The binary representation always shows in a way that every chirp is represented by a number of bits and we fixed 7 bits for this example. According to the representation of LoRa modulation in SF7, the bits are grouped by a packet of SF bits, then each packet is represented by a particular symbol among 2 forms of possible symbols. Every chirp associated with a number 10 of bits sweeps from a high frequency to a low frequency, hence the LoRa frame is the succession of those chirps transmitted in the air.

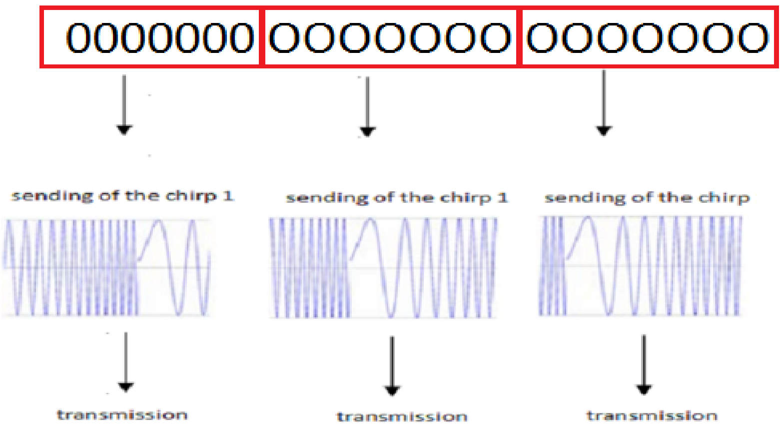

Figure 10: Emission of chirps with LoRa modulation

In LoRa, the emission time of each symbol depends on the spreading factor used. Thus, each frame is transmitted with a specific spreading factor. Accordingly, there is a relation between the communication range, the time of the emission and the SF used. Hence, the higher the spreading factor, the slower the emission and then the longer the communication range. Over a 125 kHz BW for example, the time the emission of an SF11 symbol is twice if the emission time of an SF10 symbol, so on up to SF12 for the same bandwidth.

It is not just data that is sent during a transmission LoRa. To frame the data, it is also necessary to transmit some specifications, hence the frame will be constituted by a header for the synchronization between the transmitter and the receiver, the payload that contains the user data with a maximum size between 51 and 222 bytes depending on the spreading factor and a cyclic redundancy check (CRC) to check the errors like shown in the figure below:

Figure 11: LoRa frame

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In LoRa, the larger the spreading code, the more capable of transmitting in a noisy environment. The figure below shows the signal-to-noise ratios with which we will be able to achieve a transmission, depending on the Spreading Factor used.

Table 2 : Range of spreading factors.

Spreading factor (Reg modulationcfg)	Spreading factor Chips/ symbol	LoRa demodulator SNR
6	64	-5 dB
7	128	-7,5 dB
8	256	-10 dB
9	512	-12,5 dB
10	1024	-15 dB
11	2048	-17dB
12	4096	-20 dB

LoRa WAN specification is a low, wide Area Network (LPWAN) communication protocol, and a network stack that employs LoRa physical layer to achieve long-range, its standardized by the LoRa alliance and designed to connect battery operated objects wirelessly to the internet in regional national, or global networks. LoRa wan features a maximum data rate of 27 kb/s and claims that only the gateway can collect data from multiple nodes deployed kilometers away. LoRa network classified as an LPWAN is gaining huge popularity due to its long-range, low power, and low-cost communication characteristics. Added to that, it is highly energy-efficient with 10+ years of battery life and considered as a cheap solution with the cost of a radio chipset cheaper than 2 euros. LoRa is highly suitable for IoT application that only needs to transmit a tiny data rate over a long-distance and a few times per hour [20].

According to the LoRa Alliance, which coordinates the specifications of the LoRaWAN protocol, there are LoRaWAN network deployments in 167 countries. 121 Public Telecom operators are active in 58 countries [21].

The free frequency bands, allowed for ISM applications (Instrument, Scientific, Medical) are different in every country. This is a constraint to consider, because a sensor configured on a frequency band, will generally not work on other frequencies, at least without changing the configuration.

LoRa WAN network implementation is based on the star topology and basically on the star of-star the network. the benefits of using star topology are preserving battery life and decreasing the complexity of the network meanwhile the nodes do not have to propagate or forward other nodes' data, the nodes receive only their own data without any exchanging between devices.

According to Figure 18, that shows several components are defined in a LoRaWAN as end-devices, gateways, network server, and applications.

1. End-devices perform the communication gateways using LoRa and LoRaWAN technologies.

2. Gateways dispatch the LoRaWAN frames from the end-devices to a network server using a back-haul interface with higher throughput, usually Ethernet, 3G/4G, satellite, or Wi-Fi.

3. The network server decodes the packets sent by the devices, performing security checks and adaptive data rate, thus generating the packets that should be sent back to the devices.

4. Each application receives data from the network server. It should decode the security packets and uses the information to decide the action in the application [22]

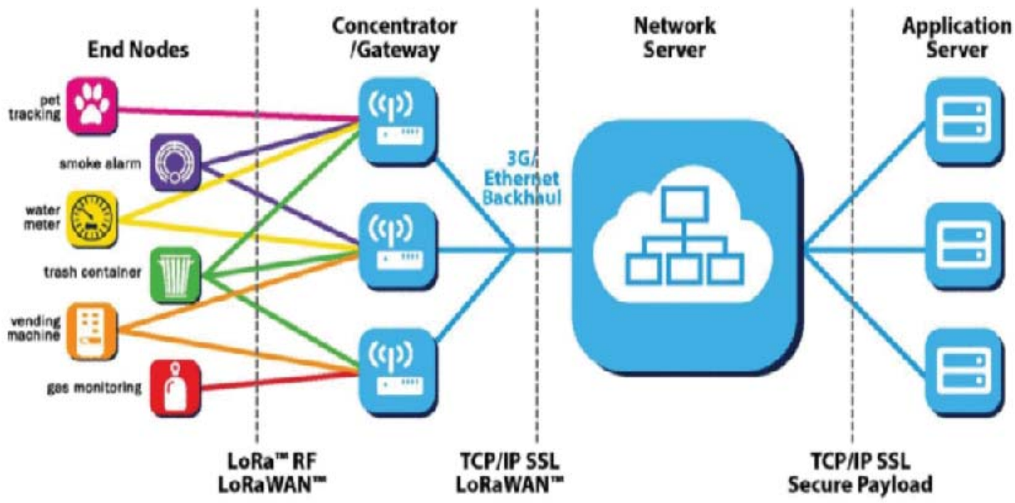

Figure 12: Architecture of LoRa WAN networks [22]

Figure 19 shows a simplified LoRaWAN frame and that the header of the LoRa protocol and a LoRaWAN header has been added. This LoRaWAN header must be transmitted and therefore increases the transmission time while the number of useful bits is the same. therefore, reduces the useful flow of transmission [21].

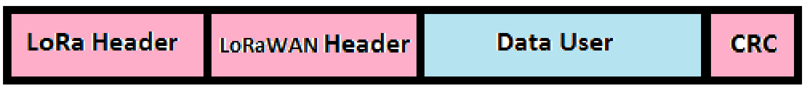

Figure 13: LoRa Frame

For the use of the LoRaWAN protocol, additional protocol layers have been added. Each layer adds a service, the highest layers represent the layers closest to the user then the lowest layers represent the layers which are the transmission medium, the two layer application and MAC

(Medium Access Layer) constitutes the LoRa WAN protocol which will be transmitted on the internet when this frame will pass the gateway, thus a different header will pass in the frame, a header that allows the transmission of frames on the internet, an IP header. Hence the content of the LoRa WAN frame will be completely preserved.

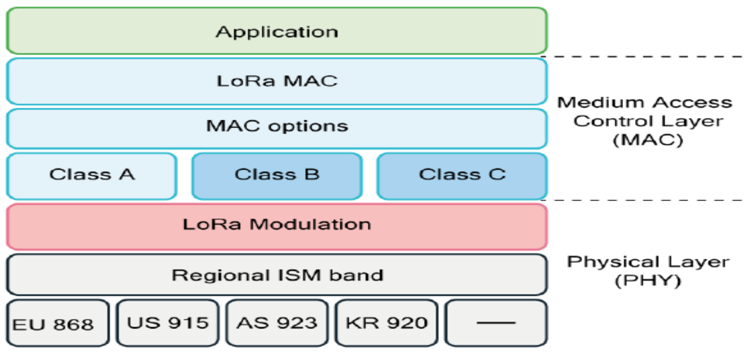

Figure 14: LoRa WAN layers [23]

For the use of LoRaWAN protocol, additional protocol layers have been added. Each layer adds a service. When it is sent to the frame, the user data is therefore encapsulated in each lower layer until transmission. The detail of the whole LoRaWAN frame per layer is described in Figure 21 [24].

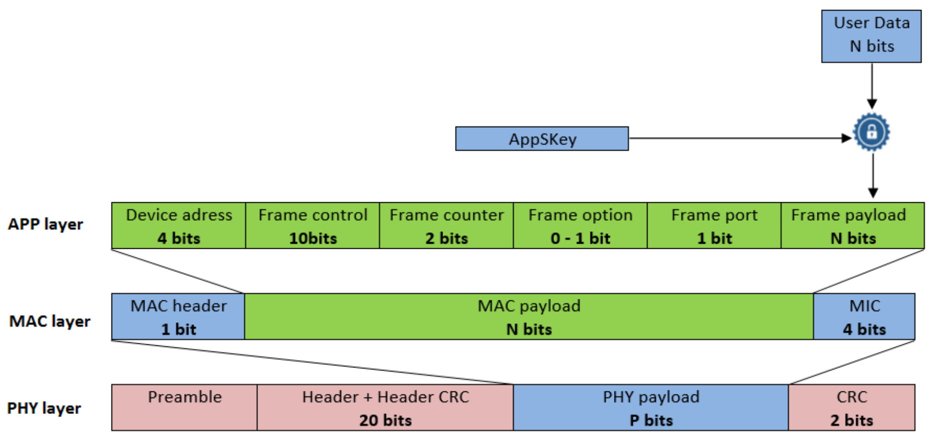

Figure 15: Frame of the different layers

The Application layer contains user data. Before encapsulating them, they are encrypted with the Application Session Key (AppSKey) to secure the transaction.

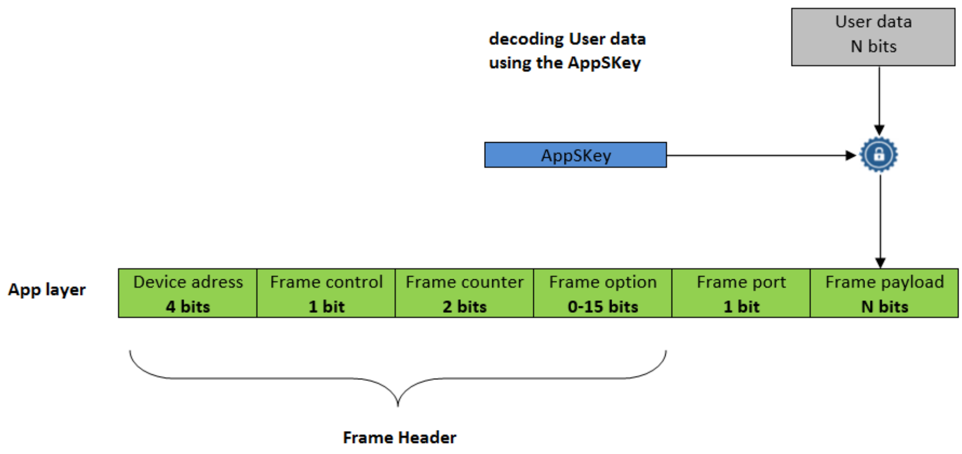

Figure 16: LoRa WAN application frame

-MAC layer frame details:

This frame is authenticated using the MIC field (Message Integrity Control), it is made up of:

1. MAC Header
2. MAC Payload: Contains all the application protocol.
3. MIC: Message Integrity Controol, for frame authentication.

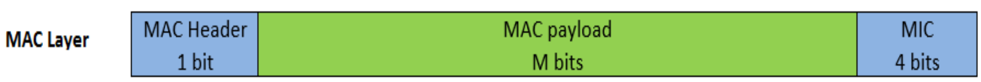

Figure 17: LoRa WAN MAC layer frame

The choice of when to issue LoRa Devices is easy. When an equipment must transmit, it does so without control and does not check whether the channel is free. If the package was lost, it will simply retransmit it after a random amount of time. The physical layer is represented by the transmission of the following frame in the figure below:

Preamble	Header + Header CRC (optional) 20 bits	PHY payload P bits	CRC 2 bits

Figure 18: Physical layer LoRa frame.

The preamble is represented by 8 symbols + 4.25. The time of the Preamble is therefore 12.25 Tsymbol. The header (optional header) is only present in the default transmission mode, it is transmitted with a Coding Rate of 4/8. It indicates the size of the data, the Coding Rate for the rest of the frame and it also specifies whether a CRC will be present at the end of the frame.

The physical Payload contains all the information of the LoRa MAC layer. In this case, the CRC is used for error detection of the frame.

In end devices, the downlink communication latency is an important part to determine the size of the power battery in use. LoRaWAN is an asynchronous protocol based on ALOHA (Additive Links On-line Hawaii Area), hence an end device can “wake up” at programmable intervals of time to check the downlink, in a synchronization window with the network to reduce communication latency and consumption, respectively. LoRaWAN end-node devices have three modes of operation, the device classes can negotiate network downlink communication latency versus battery lifetime: Class A (the default), Class B, and Class C (both optional). These three modes with different capabilities describe how the end-node device can access a wireless network.

- Class A (bidirectional) - All LoRaWAN Devices are class (A) Each Device can transmit (Uplink) to the Gateway without checking the availability of the receiver. If the transmission fails, it will be reissued after some time. This transmission is followed by 2 noticeably short reception windows. The Gateway can then transmit during "RX Slot 1" or "RX Slot 2", but not both.
- Class B - Devices behave the same as Class A Devices, but other Reception windows are scheduled at specific times. To synchronize the windows reception of the LoRa Device, the Gateway must transmit beacons on a regular basis.

- Class C - The devices use receiving windows continuously, between 2 Uplinks. It has high power consumption, lowest latency sending/receiving unicast and multicast messages [22].

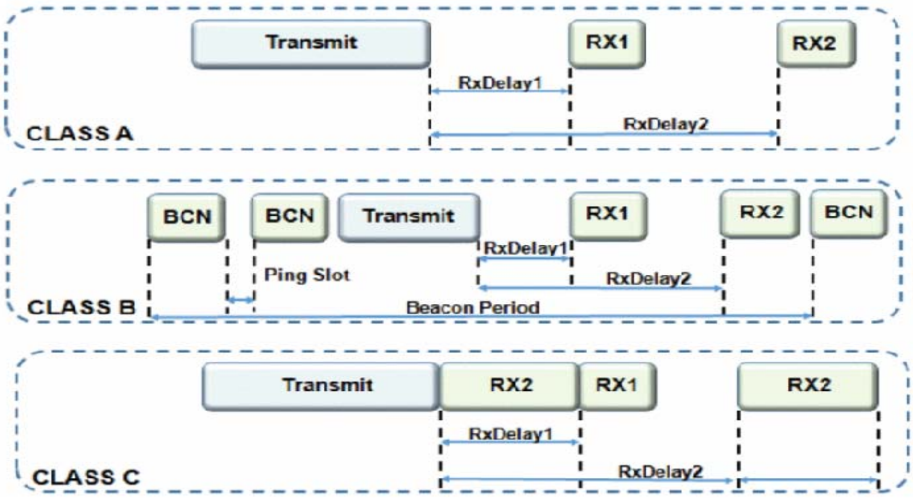

Figure 19: LoRa WAN Classes [25]

4.4.1 LoRa WAN Security

LoRaWAN specifies several security keys: Nwskey, AppSkey and AppKey. All keys have a length of 128 bits.

The Network Session Key (Nwskey) has been used for authentication between the LoRa Device and the Network Server. For the reason to perform this authentication between the Device and the Network Server, a MIC fiel (Message Integrity Control) is added to the frame. It is calculated based on the data transmitted and the Nwskey. On receipt, the same calculation is carried out. If the Nwskey is equivalent in the Device and in the Network Server, then the two calculated MICs must match. The Application Session Key (AppSkey) is used for encryption between the LoRa Device and the Application Server. The encrypted data will then be decoded upon receipt on the Application Server if it has the same key.

Over The Air Activated devices (OTAA) use the Application Key (AppKey) to obtain the two session keys through the activation procedure, it's only known by the device and by the application

128-bit AES keys allow the encryption of information to be transmitted in LoRaWAN. Despite this, a known Wireless attack of REPLAY may happen and allows Hackers to record encrypted frames circulating on the LoRa network to re-transmit them later, even so, if they do not understand the content (the frames are encrypted), the data that is transported is well understood by the Application Server. To avoid this, the LoRaWAN frame integrates a variable field called Frame Counter. This is a 2-byte number numbering the frame. The Server will accept a frame only if the Frame Counter received is greater than the Frame Counter previously. So, if the Hacker retransmits the frame as it is, the Frame Counters will be equivalent, so the frame will be refused. If the hacker decides to modify the Frame Counter field with a random value, the authentication will fail because the calculation of the MIC with the Network Session Key will no longer be valid [26].

4.4.2 Covered area of LoRa node:

The emitted power (PE) will be attenuated in the air according to the following formula**:**

$$\boldsymbol{attenuation = 10\ log\ (distance^2 \times frequency^2 \times 1755)}$$

- Attenuation in dB
- Distance in km
- Frequency in MHz

$$Distance = \sqrt{\frac{10^{\frac{attenuation}{10}}}{1755 \times frequency^2}}$$

The link Budget being the maximum attenuation that a transmission can withstand, can deduce the distance by replacing the attenuation by the link budget:

$$Distance = \sqrt{\frac{10^{\frac{link\ budget}{10}}}{1755 \times frequency^2}}$$

Our model RFM96W have a link budget of 168 dB hence, our theorical distance is 6,907 km.

Chapter 5 Practical implementation

5.1 Introduction

Fertigation is a crop growing method that consists of the precise injection into crop-growing lines of a nutrient solution that commonly consists of a mixture of three basic components (nitrogen, phosphorus, and potassium) diluted in water. This nutritive suspension is widely used to deliver to the plants with a certain frequency content that depends on the plant's type, its vegetative state, and environmental conditions.

Figure 20: Production of strawberry by fertigation

Our work aims at effectively controlling and optimizing this fertigation process by providing the agents in charge of the project with accurate information about the temperature and humidity across the crop growing lines.

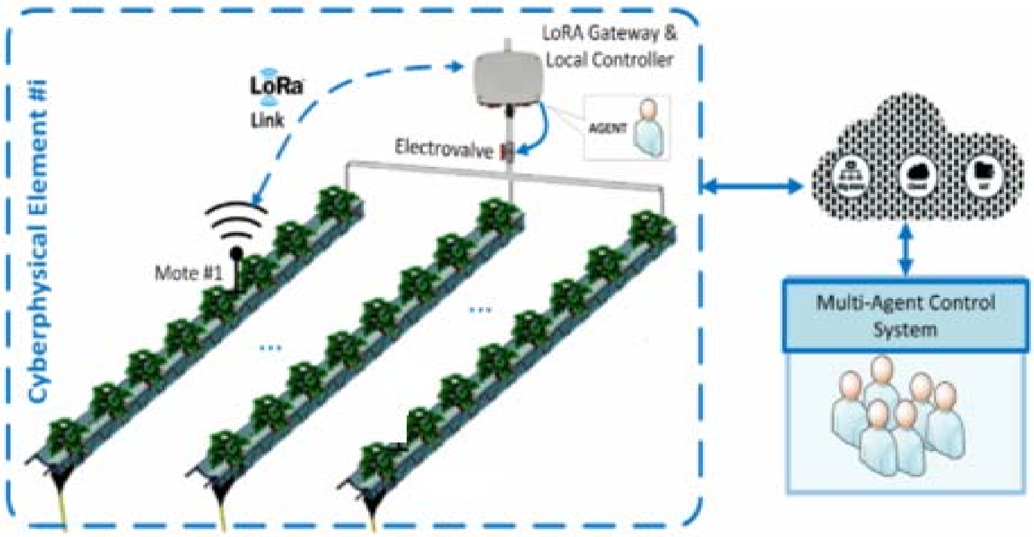

Figure 21: System overview

In the figure above, the architecture of the project is shown. On the left, the strawberry growing lines contain monitoring nodes. In each node, a sensor is implemented to detect the environmental changes and to send data directly to the gateway. The gateway collects all the data sent by the nodes this data is exchanged via the LoRa network. The gateway should be in a place where a connection can be provided. Once the data is received from the nodes, it is computed, converted, and sensed to our things network, which is a free cloud for LoRa devices on the internet, allowing easy access for data from any point whenever we need it. On the right, the dashboard which can display graphically the data stored by the agents.

5.2 LoRa gateway

For the gateway, we used as it was mentioned before the Raspberry Pi 3 B+ with the LoRa RFM95W receiver that is linked to The Things Network cloud.

5.2.1 The RFM96W

Figure 22: RFM96W

The RFM95W features the LoRa Long-range modem, providing an ultra-long range spread spectrum communication and low power consumption, it can achieve a sensitivity of over 148 dBm using a low-cost crystal and bill of materials. The high sensitivity combined with the integrated +20 dBm power amplifier yields an industry-leading link budget making it optimal for any application requiring range or robustness. By using the definition of the Link Budget, we find the 158 dB announced in this documentation (20 dBm + 138 dBm). The RFM95 (W) delivers exceptional phase noise, selectivity, receiver and linearity for significantly lower current consumption than competing devices.

The features of the three product variants are presented in table below:

Table 3 : RFM95/96/97/98(W) Device Variants and Key Parameter.

Part Number	Frequency Range	Spreading Factor	Bandwidth	Effective Bitrate	Est. Sensitivity
RFM95W	868/915 MHz	6 - 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to - 148 dBm
RFM97W	868/915 MHz	6 - 9	7.8 - 500 kHz	0.11 - 37.5 kbps	-111 to - 139 dBm
RFM96W/RFM98W	433/470MHz	6- 12	7.8 - 500 kHz	.018 - 37.5 kbps	-111 to - 148 dBm

5.2.2 installing the Raspbian in the raspberry pi:

Raspberry Pi does not come with a pre-installed operating system. There are plenty of operating systems available for the Raspberry Pi and we can choose on like in the figure below.

1- Open the browser and go to the official raspberry pi download page and download the Raspbian as shown in the figure below:

Figure 23: Raspbian installation

2- After downloading the ZIP file unzip, it using 7Zip for windows.

- **Formatting the SD card:**

Before writing the Raspbian to the SD card we have to format the card using SD formatter:

1. Insert the microSD card into the adapter. Then insert the SD card adapter into the SD card port on PC.

2. Start SD Card Formatter and under “Select card,” select the SD card from the list.

3. Select “Overwrite format.” Under “formatting option”

4. Click the Format button to start formatting.

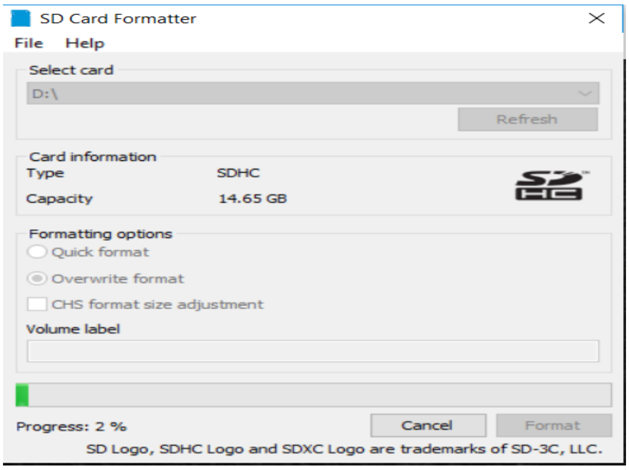

Figure 24: SD card formatting

- Writing Raspbian Stretch LITE to the SD Card:

1-Install Etcher on your computer and then run the program to open it.

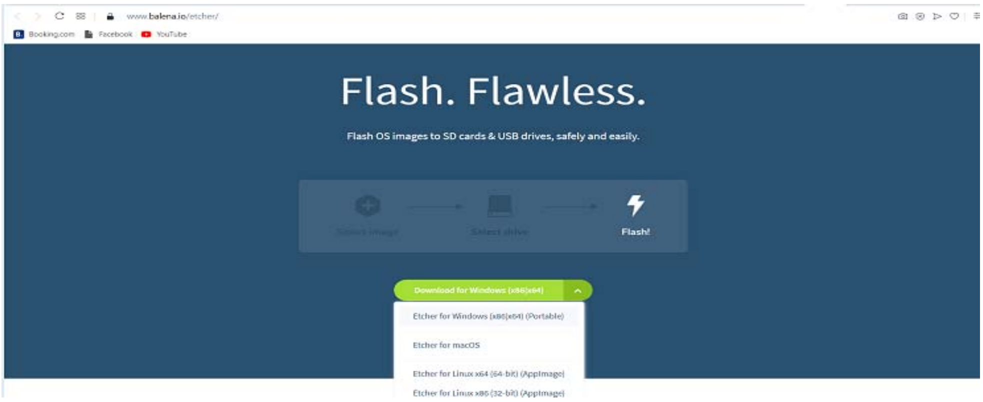

Figure 25: Etcher install

3- In the Etcher window click the "select image" button to browse the downloaded Raspbian image (Zip) from the PC.

4- Select the Micro SD card by clicking the "select drive" button.

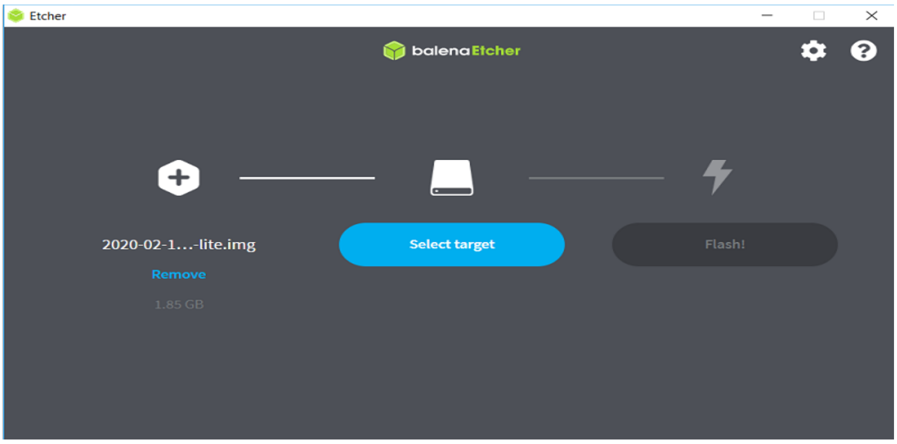

Figure 26: Selecting the SD card in Etcher

5- Click the "flash!" button to start writing data to the Micro SD card.

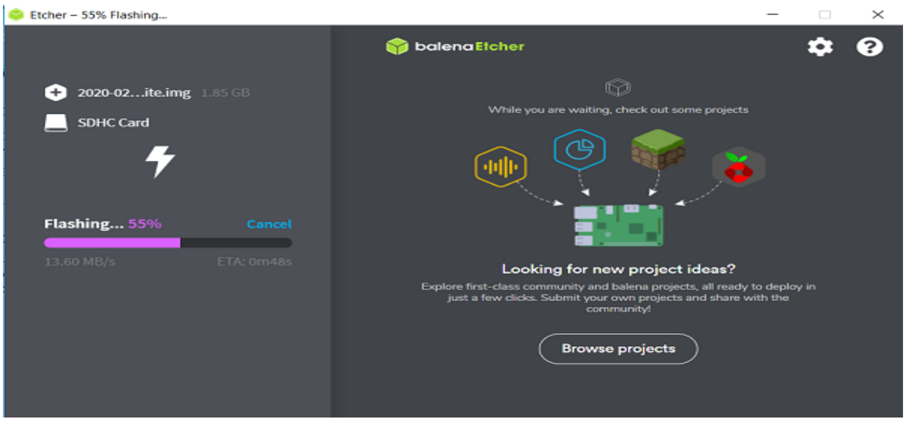

Figure 27: Flashing process in Etcher

6- Remove safely the SD card and put it in the raspberry slot.

5.3 Building the Gateway:

The Raspberry Pi-based LoRa gateway can be built with the following items:

- Raspberry pi 3 B+ with Raspbian image written.
- Wall adapter power supply
- LoRa RFM95W radio transceiver

Figure 55 shows the wiring connection between each component of our gateway.

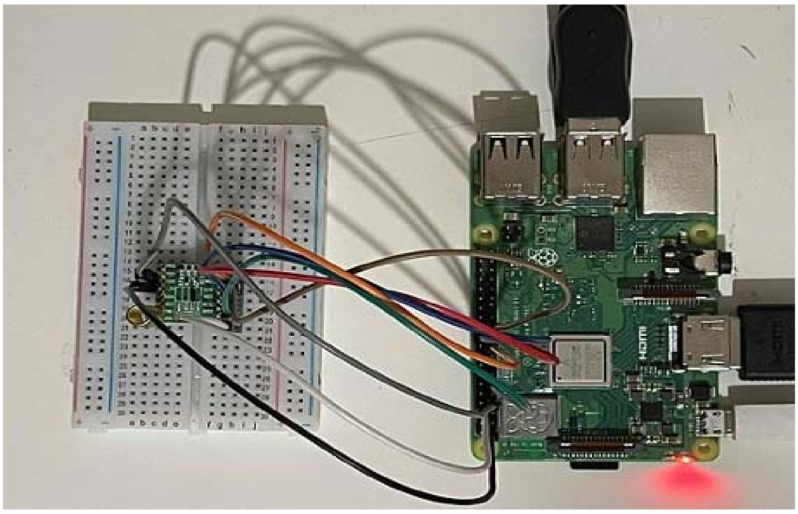

Figure 28: LoRa gateway

The connections to make:

Table 4: Gateway components.

RFM95W	Raspberry pi 3 B+
3.3V	1
GND	6
DIOO	7
RESET	11
NSS	22
MOSI	19
MISO	21
SCK	23

1-Before SSHing into the Raspberry Pi, first we should connect it to our Wi-Fi and know its IP by typing the "ifconfig" command like shown in the figure below:

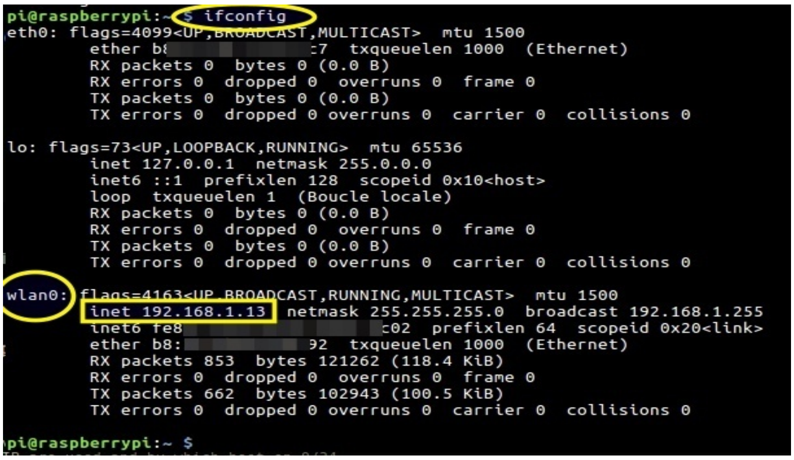

Figure 29: IP address of the raspberry

2- Download and Open PuTTY, and in the PuTTY Configuration window, under Host Name, we type the IP address of the Raspberry Pi. The default port number for SSH is 22, we click on the “Open” Button (Figure38).

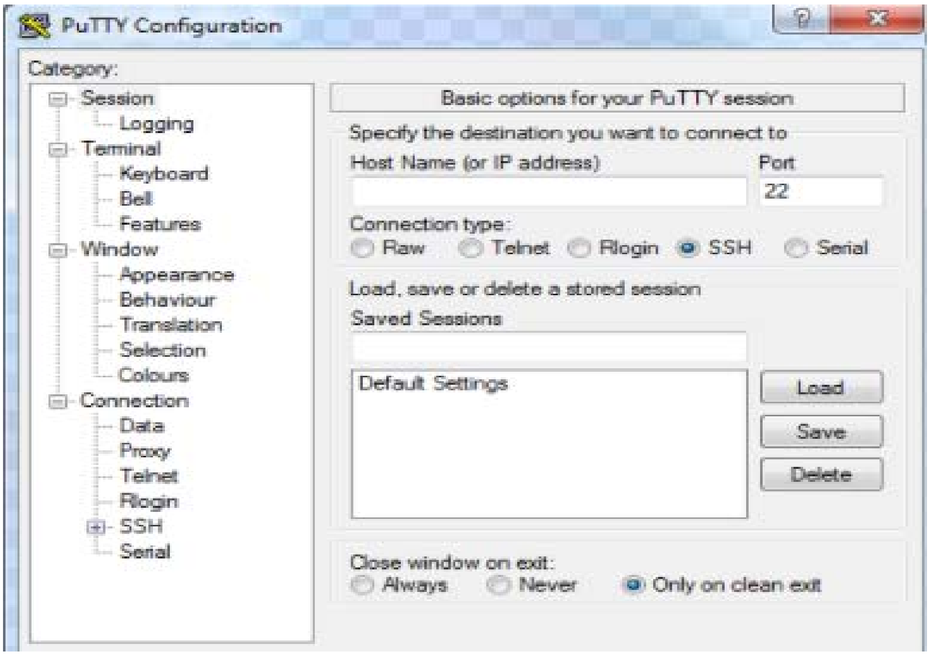

Figure 30: PuTTY Configuration

3-The default login for the Raspberry Pi after connection with Putty and typing the login and the password of the Raspbian are as follows (Figure 39):

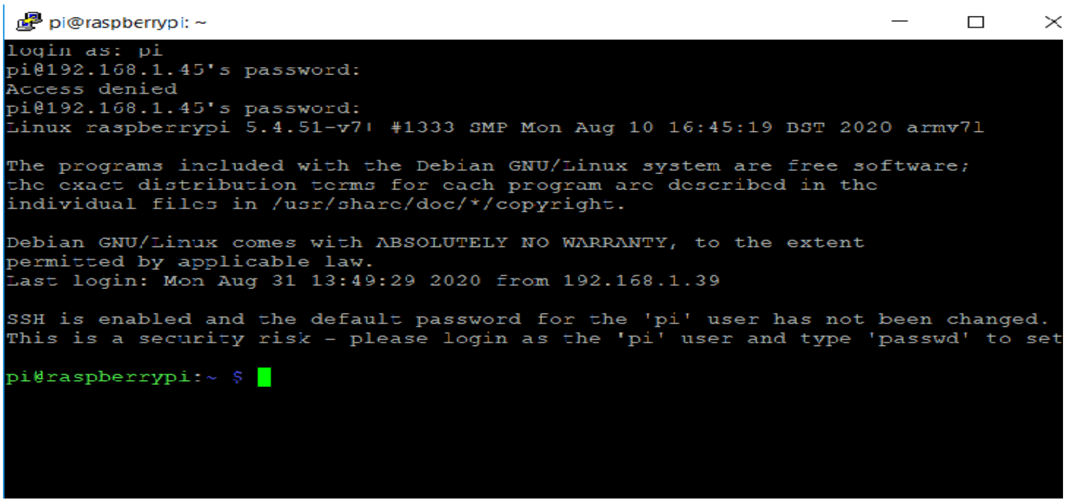

Figure 31: Login into the raspberry pi thought SSH

To allow the Raspberry Pi to communicate with the LoRa radio transceiver module, you should enable the SPI interface on the Raspberry Pi. Type the following command to open the Raspberry Pi Software Configuration Tool:

"Sudo raspi-config"

In the Raspberry Pi Software Configuration Tool, choose Interfacing Options. Then click the Enter key on the keyboard

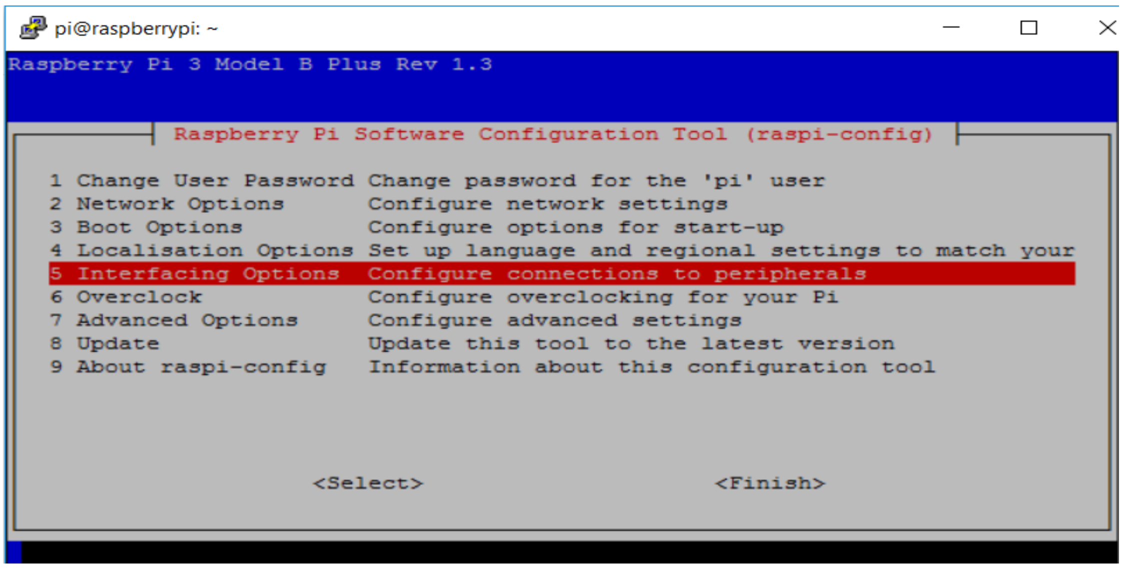

Figure 32: Interfacing option

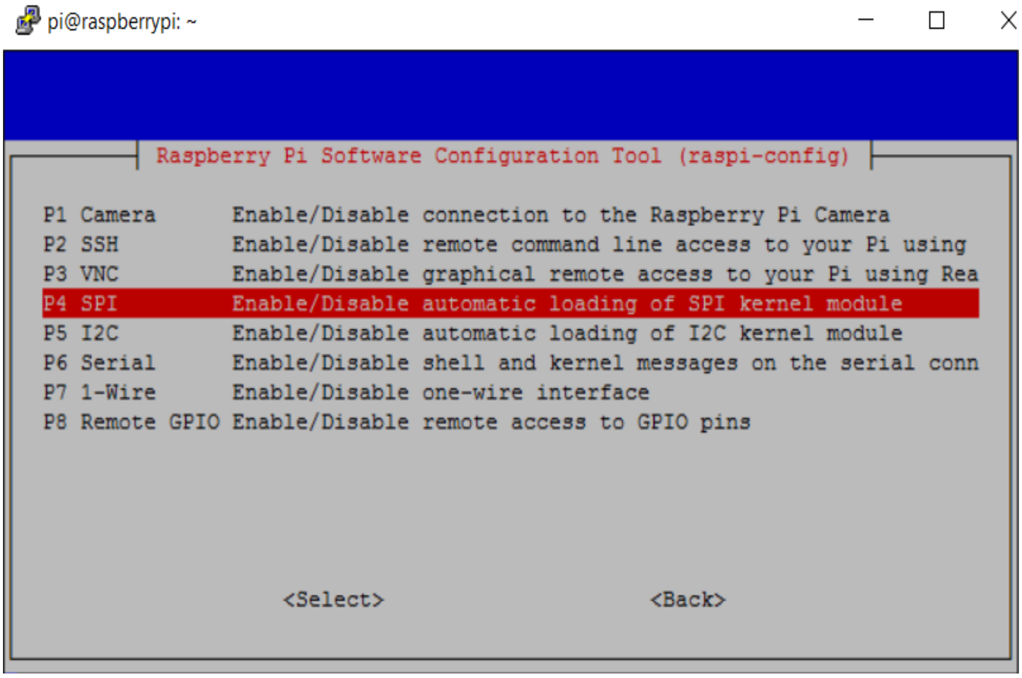

Figure 33: SPI enabling

3- Reboot the Raspberry Pi with the following command:

'Sudo reboot'

- **Installing Wiring:**

The Wiring library allows to easily interface with the GPIO pins of the Raspberry Pi. It also supports I2C and SPI. We can use the command "sudo apt-get install wiringpi"

to install the Wiring library on the Raspberry Pi.

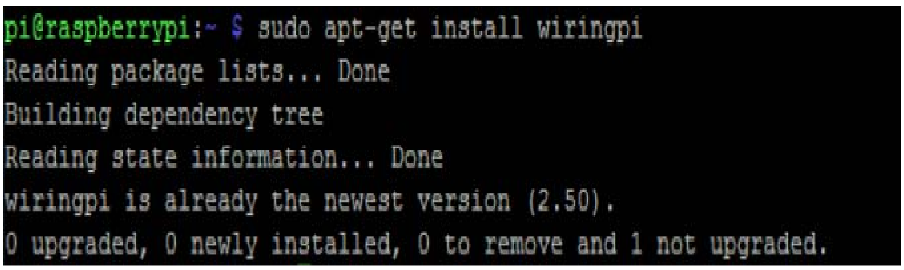

Figure 34: wiring install

- **Installing and configuring a Single-Channel Packet Forwarder:**

Single-channel packet forwarder software has a spreading factor from SF7 to SF12 and can listen on a configurable frequency. we will install the single-channel LoRaWAN gateway software following the steps below:

1. Install Git using the following command:

   sudo apt-get install git

2. Clone the repository using the following command:

git clone https://github.com/tftelkamp/single_chan_pkt_fwd

Figure 35: Install of the single-channel

3- Getting the IP address for the router address, router.eu. thethings. network, use the following command (we will need it after): ping router.eu. thethings. network

Figure 36: Address IP of TTN

4- Use the following commands to open the main.cpp file in the single_chan_pkt_fwd directory:

~cd single_chan_pkt_fwd nano main.cpp

```
pi@raspberrypi:~ $ cd ~/single_chan_pkt_fwd
pi@raspberrypi:~/single_chan_pkt_fwd $ nano main.cpp
  GNU nano 3.2                        main.cpp
```

Figure 37: Channel configuration

5-Searching for the position (needed after):

Open google maps to check our location like shown in the figure below:

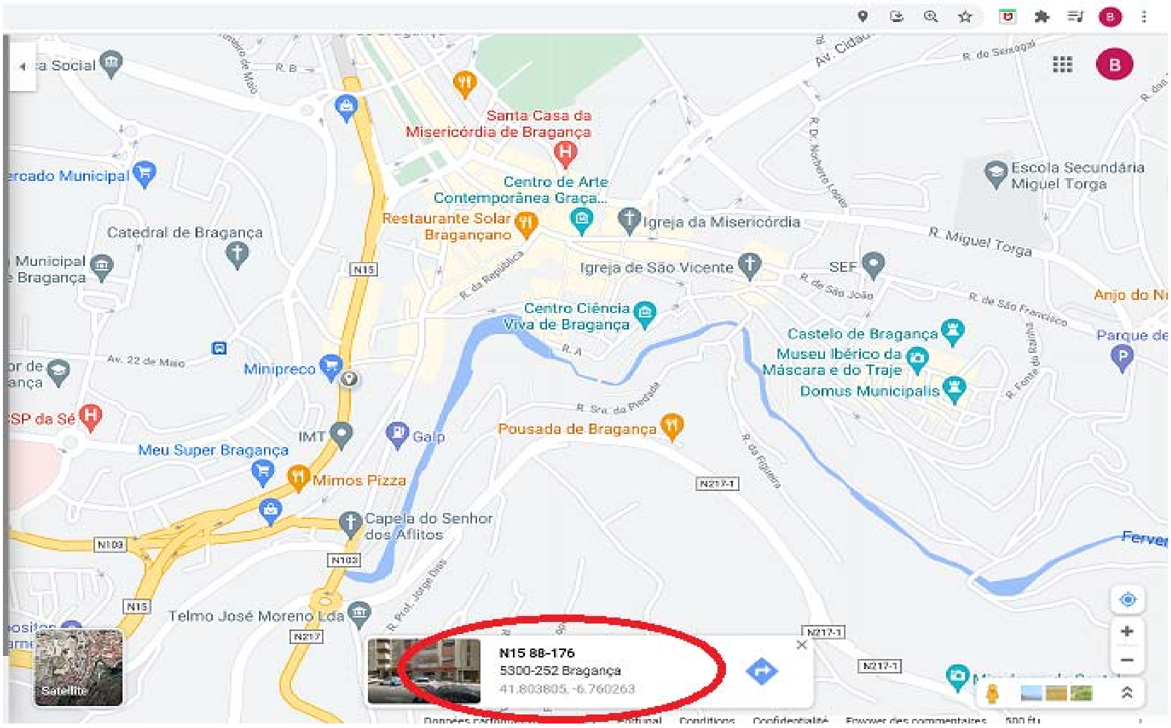

Figure 38: Channel configuration

6- Configure by:

- Changing the right frequency
- Changing the coordination of our position
- Changing the IP address of the things network

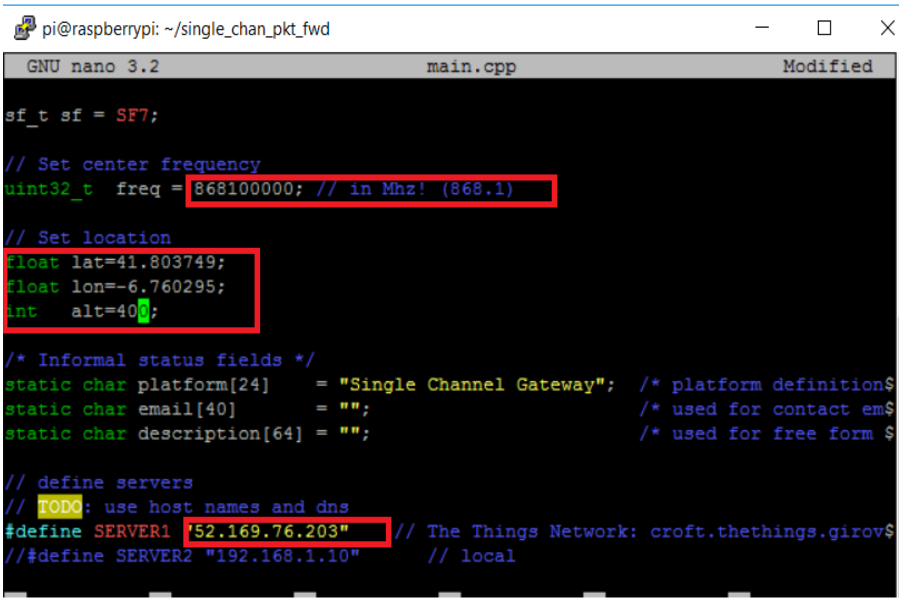

Figure 39: Our location by google Maps

7- Save the file by pressing Ctrl+X, followed by Ctrl+O.

8- Now you can compile the code using the following command: “Make”

9- After compiling the code, run the packet forwarder using the following command:

“. /Single_chan_pkt_fwd”

10- You will get output something similar to Figure (48). This shows the status of the RFM95w LoRa radio transceiver module as “SX1276 detected, starting.”

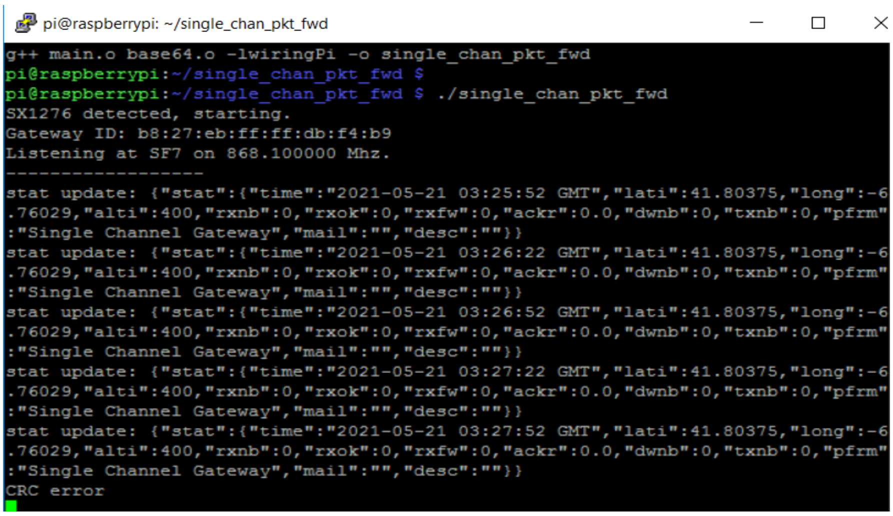

Figure 40: Console output for the single-channel packet forwarder

13- Note the gateway ID. We need the gateway ID to configure the gateway with the Things Network. The autogenerated gateway ID for this gateway is b8:27: eb: ff: ff:db: f4: b9.

- **Registering the Gateway with the Things Network:**

1- Go to the Things Network (https://www.thethingsnetwork.org/) and click the Sign-Up but we have already our account with the name "LoRaUserR7", thus to start the registration we click on "console" like shown in the figure below:

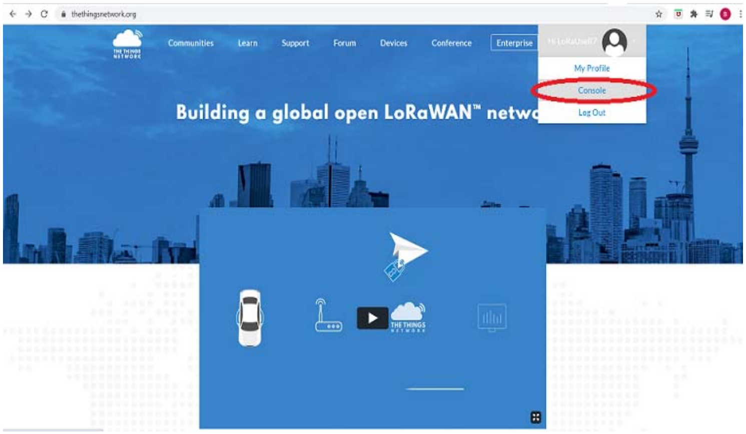

Figure 41: Registration of the gateway in TTN

2- On the console landing page, click Gateways simply click on "gateway"

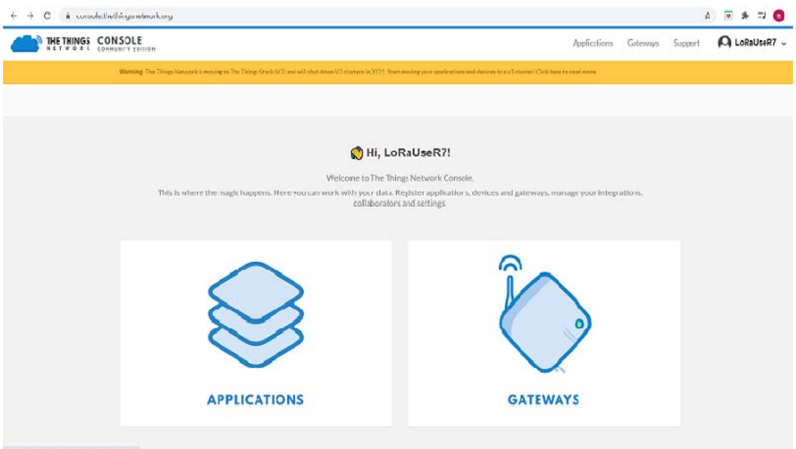

Figure 42: choosing the gateway icon

3- Click the "register gateway" link:

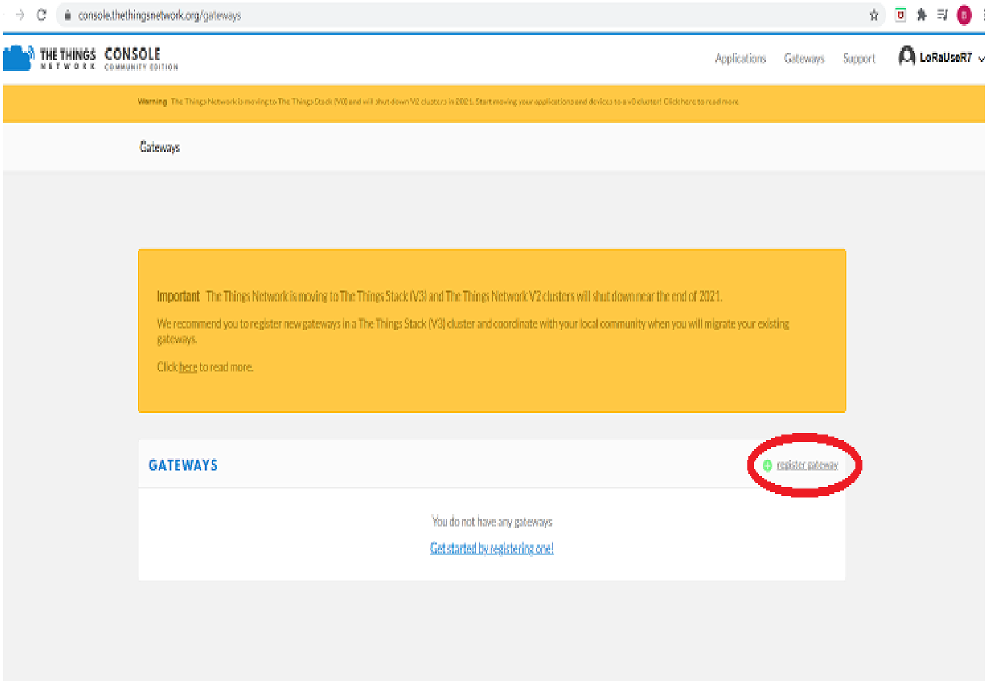

Figure 43: Register gateway step

4- On the register page, under the Register Gateway section, fill out the form with the following information:

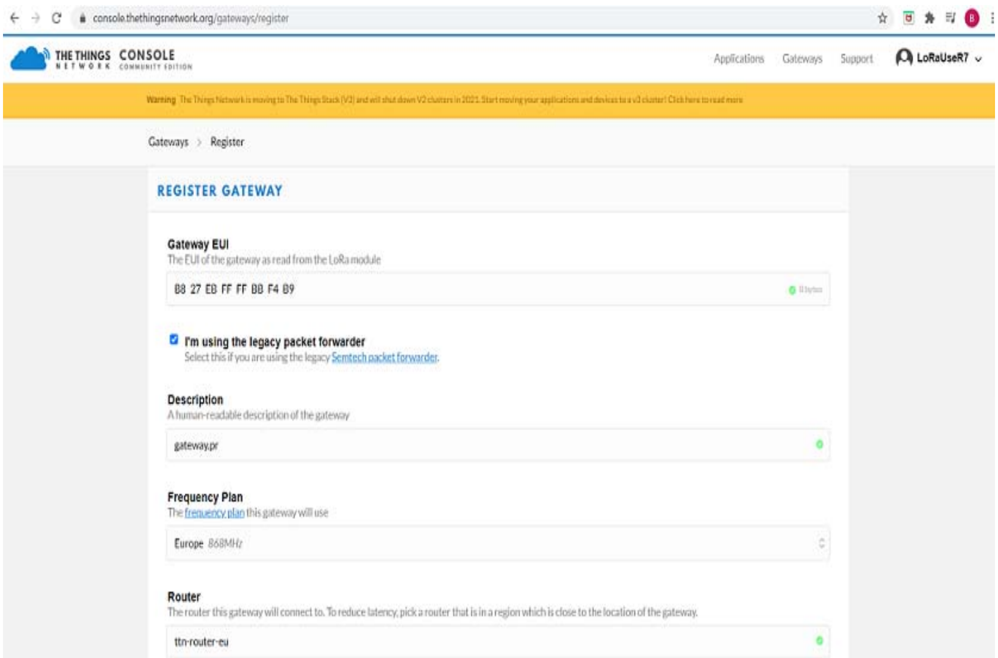

Figure 44: Information gateway filling

- Gateway ID: This is a unique human-readable identifier for the gateway. Use the gateway ID generated by the single-channel packet forwarder and type it (in our case we type “**b827ebffff7a51d5**”).
- Description: Type in a name for your gateway (in our case we wrote **My First Raspberry Pi Gateway**) *Frequency Plan*: Choose the frequency plan from the drop-down list to use with our gateway’s LoRa radio transceiver module which is *868 MHz.*
- Router: Choose a router from the drop-down list to connect your gateway to the Things Network (ttnrouter-eu).
- Location: Click the map to mark the location of your gateway like shown in the figure below:

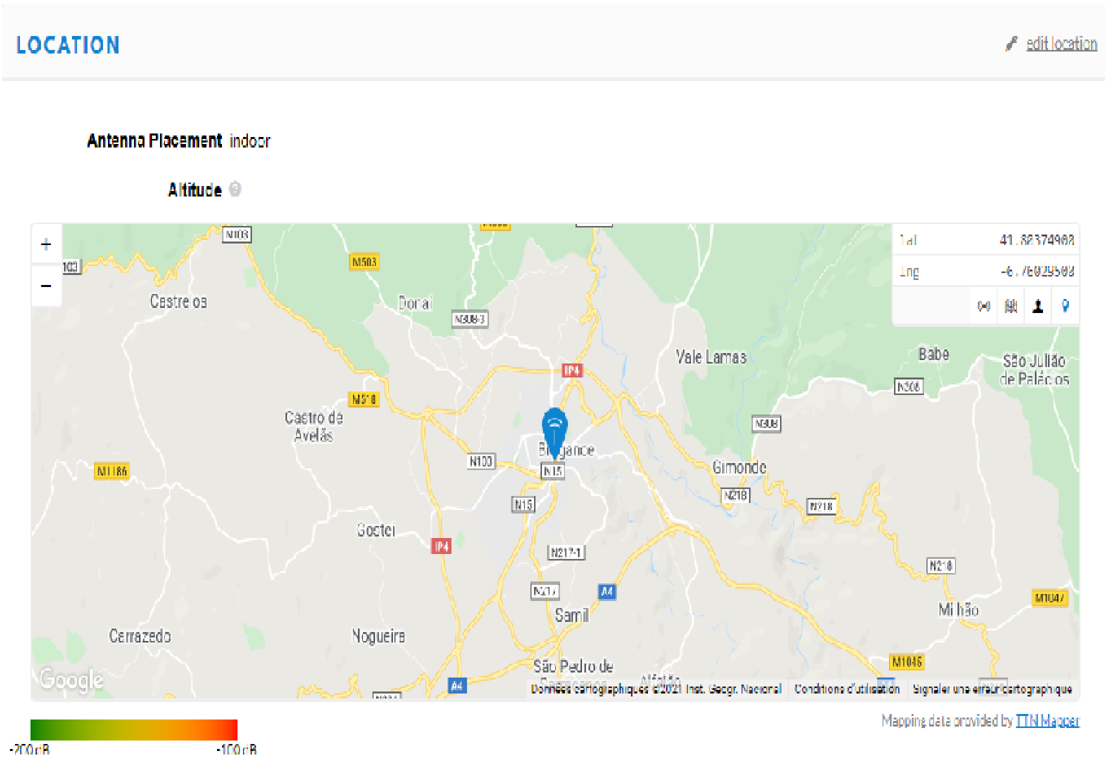

Figure 45: The location of our gateway

- Antenna Placement: Chose Indoor.

4- Click the Register Gateway button to complete the registration. We will be navigated to the gateway page.

If we want to modify the settings for your gateway, click the Settings tab. On the Settings page, under Gateway Settings section, modify the fields and finally click the "Update Gateway" button.

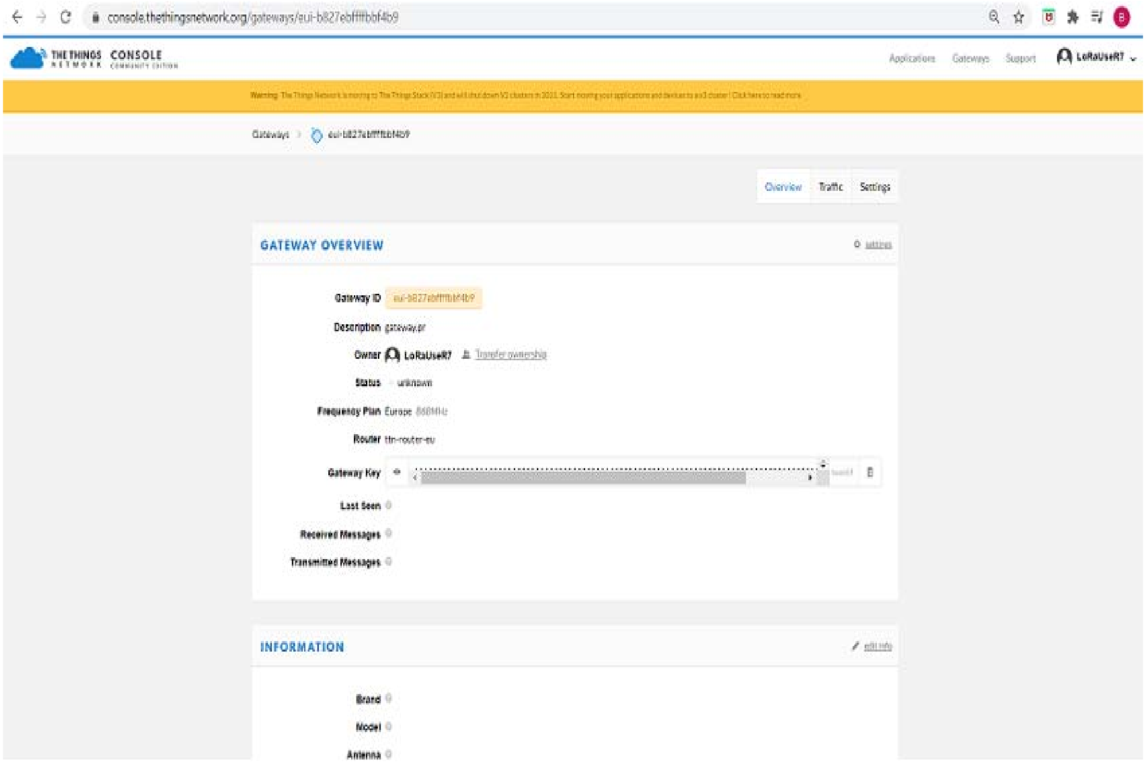

Figure 46: Overview of the registered gateway

5.3.1 The gateway role:

As was mentioned in the previous parts, in decrypting the message using the session key application. As can be seen in the figure below, our gateway is interposed between our node (LoRa device) and our network server and application server, on the LoRa device (the node) and under the servers we have represented the messages in the form of layers, the elements of the frame are put one under the others, our data of the sensors are encapsulated in a LoRa WAN frame which is then modulated by LoRa modulation.

The temperature and humidity data will be put in the application layer where the user data must be presented, this data will be encrypted with an appSkey key, the layer below(MAC layer) will add an additional service with is the authentication service, this authentication is done using the Nwskey key, then this LoRa WAN message will be modulated into LoRa and transmitted in radio frequency link towards the gateway where will be received and demodulated, thus our gateway receives the content of the message and pass it to another "IP" protocol. The message received is not analyzed at all by the gateway, hence our gateway receives data in the form of a black box, it does not have the capacity to understand it, moreover the gateway plays the role of passing the elements of a LoRa protocol to an IP protocol. The gateway is configured to send messages to a server, which will decrypt these messages. The network server will check the authentication using Nwskey. Finally, the gateway served us to pass the information of our nodes from a LoRa radio protocol to an IP protocol and pass these messages to our server (application server and network server).

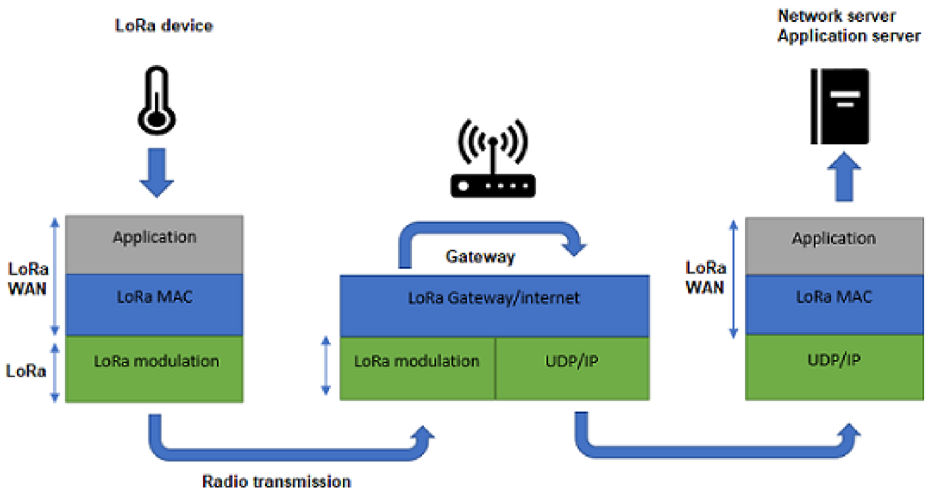

Figure 47: Gateway role

5.4 Measurement nodes

5.4.1 Hardware composition:

The system's material for the project was fixed at the beginning of the work and it's limited to "off the Shelf" components. The decisions were based on the customer's needs, the compatibility with the Arduino UNO, as well as the cost of our sensors.

5.4.2 Creation the Application:

1- After choosing the console, click Applications.

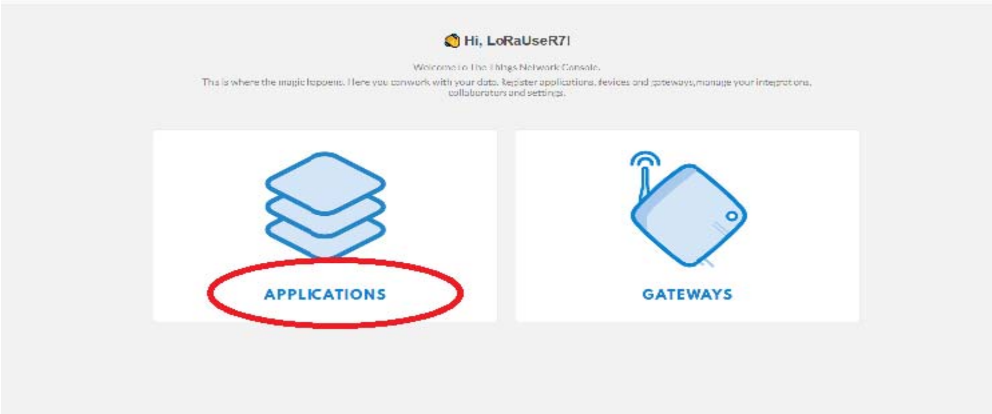

Figure 48: Creation of an application

2.Then click the “add application” link.

3. On the Add Application page, in the Add Application section, fill out the form as shown the figure below:

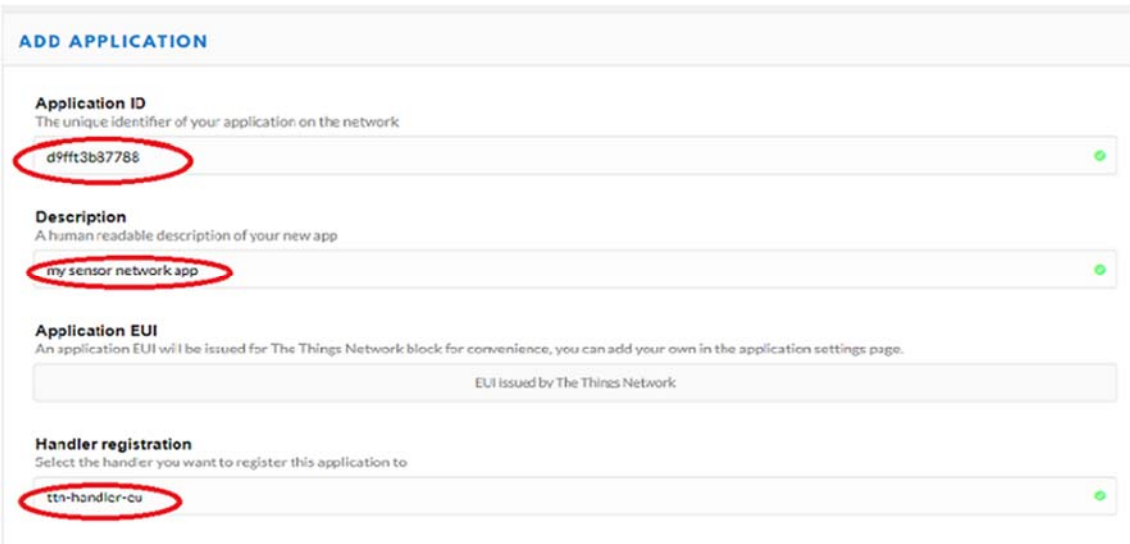

Figure 49: Filing the form

Application ID: Enter the identifier of the application (d9fft3b87788).

Description: any description of the new application (My sensor network app).

Handler registration: choose the handler of this application to (ttn-handler-eu).

4.Click the “Add application” button to add the new application in TTN. You will be navigated to the application page. Scroll down the page and locate the Devices section. Then, click the “register device” link

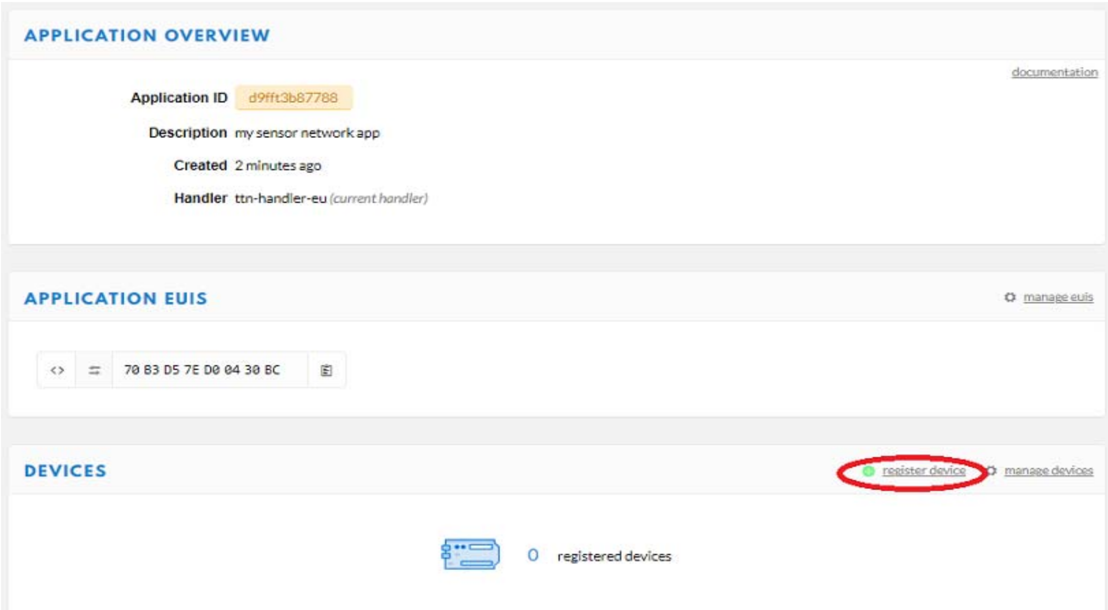

Figure 50: Application overview

5-On the Devices page, in the Register Device section, fill out the form

Device ID: the only identifier of the device in this application.

Device EUI (Extended Unique Identifier): The device EUI is the unique identifier for this device on the network it must consist of 8 bytes.

AppKey: insures the secure communication between your device and the network. It’s an autogenerated key.

App EUI: is an autogenerated identifier.

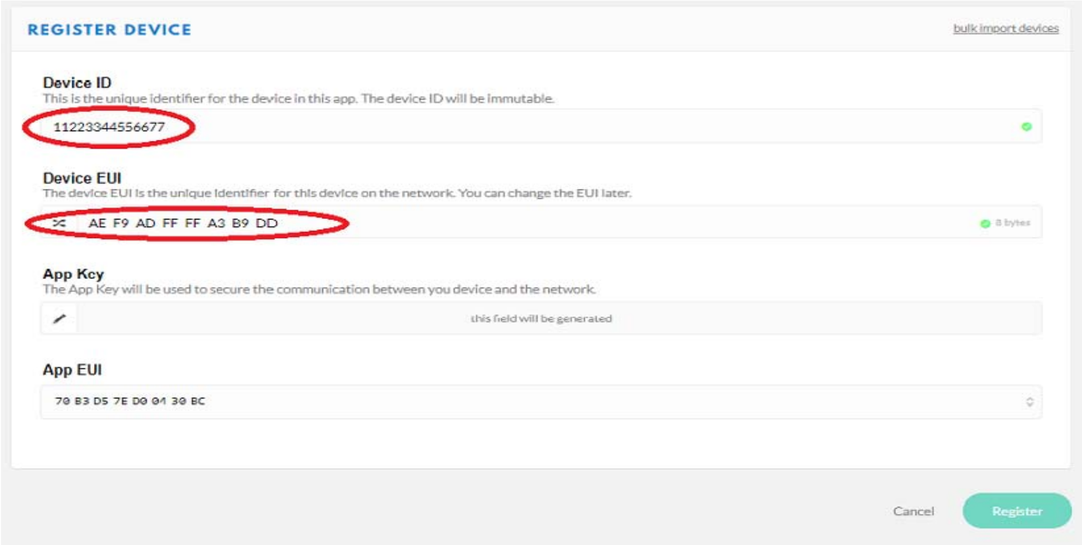

Figure 51: register the device

6. Press the Register button to register the device.

7. Open device page, choose the Settings tab.

8. On the Settings page, in the Settings section, click ABP as the activation method. This means activating a device by personalization. Then press the Save button. This will generate the device address, network session key, and app session key.

Figure 52: Activation method

9. We can finally view the autogenerated network session key, device address, and app session key on the device page, in the Overview section.

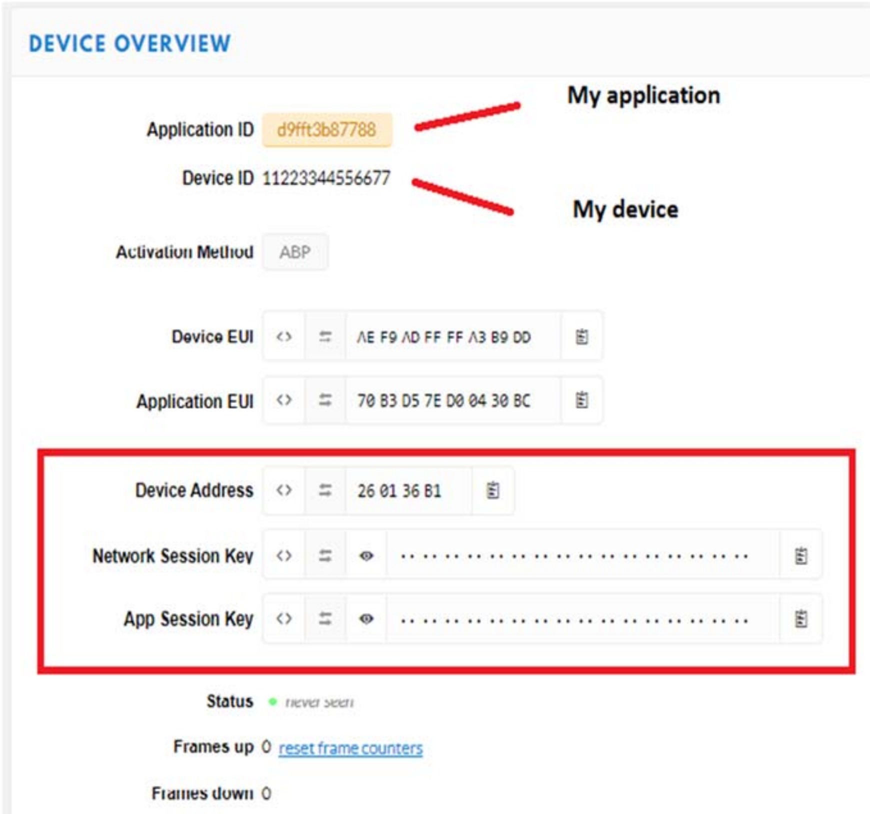

Figure 53: Device overview

- **connection of the node:**

Table 5 : Node components connection

Arduino Uno	RFM96W	DHT11
2	G0	
3	G1	
4	G2	
5	RST	
6	CS	
8		DATA
11	MOSI	

12	MOSO	
13	SCK	
5V		VCC
GND		GND

1- In arduino code make sure to put the right NWKSKEY, APPSKEY and the DEVADD From the TTN like shown in the figure below:

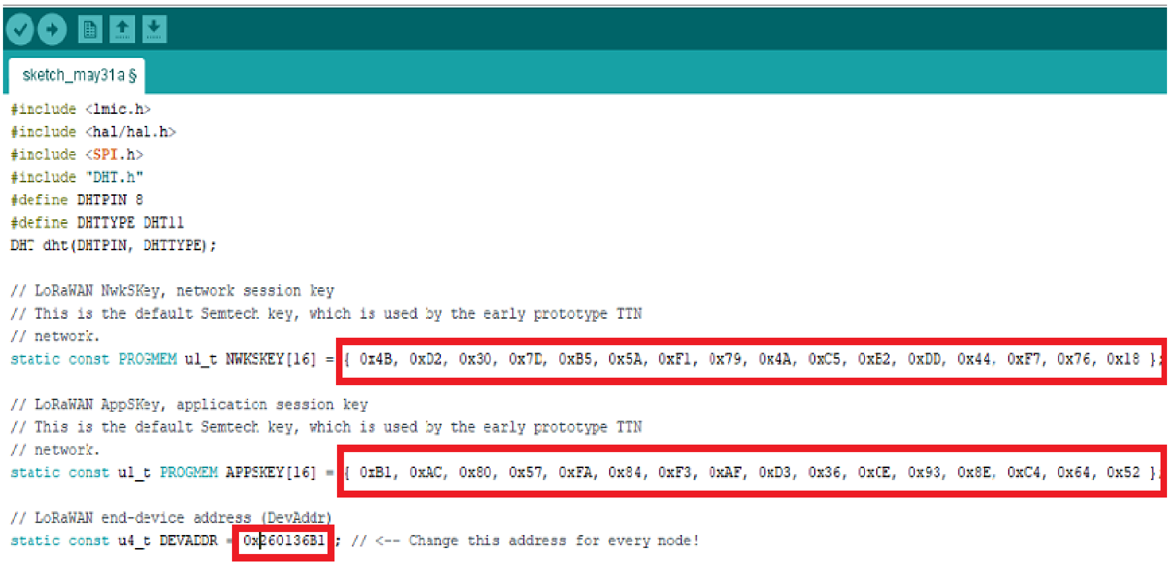

Figure 54: Portion of node code

1- Make sure that the declaration of the pin is right like shown in the figure:

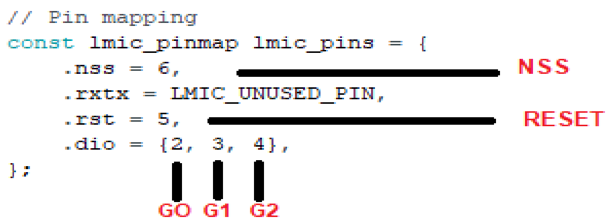

Figure 55: Node code portion

5.5 The Paas and dashboard:

Like most protocols, HTTP involves the transfer of information between a client and a server. The client and the server are two remote entities that want to talk to each other. The client makes requests, and the server responds. This notion of Client - Server is enough analog to the one you have in a restaurant. The client calls out to the server to specify his need, so it issues a request. The server processes this request by delivering the content. The customer and the server can be of any type: mail, web, files, etc.

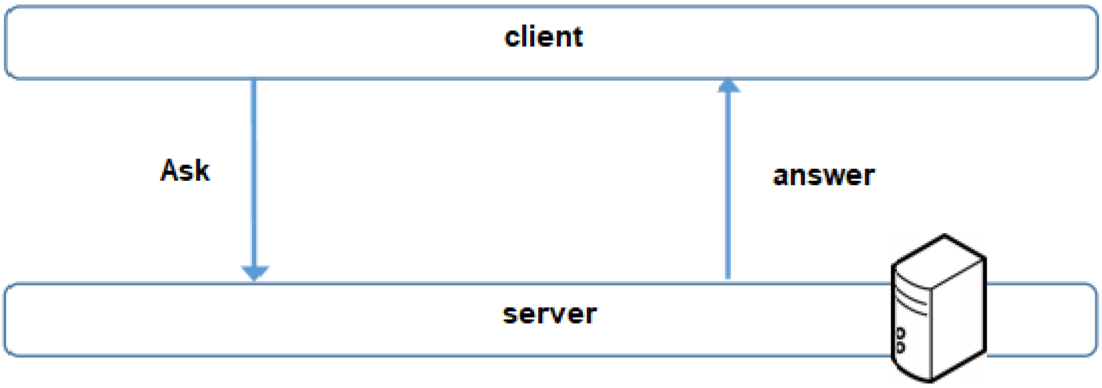

Figure 56: Client-server mode

To retrieve data from the LoRaWAN (TTN) server on our application, the first idea is to make a request (1) to TTN from our Application to provide us with this data. This HTTP protocol request is called an HTTP GET request. When you make an HTTP request GET to a web server, it returns the content of the HTML page it contains to you. Here, TTN which will have therefore the server role will return LoRa (2) data. Thus, in this case, we have TTN playing the role of the server and our application which plays the role of the client.

5.5.1 Installation of HTTP services for the Uplink:

Passing to set up to extract data present on the LoRaWAN servers in order to repatriate them to our application, hence we need to set up an HTTP server on our LoRaWAN servers and an HTTP client on our application.

Starting by setting up the HTTP server on TTN. For this we have to get in our TTN console. TTN> Applications> Application name> Integration> Data Storage

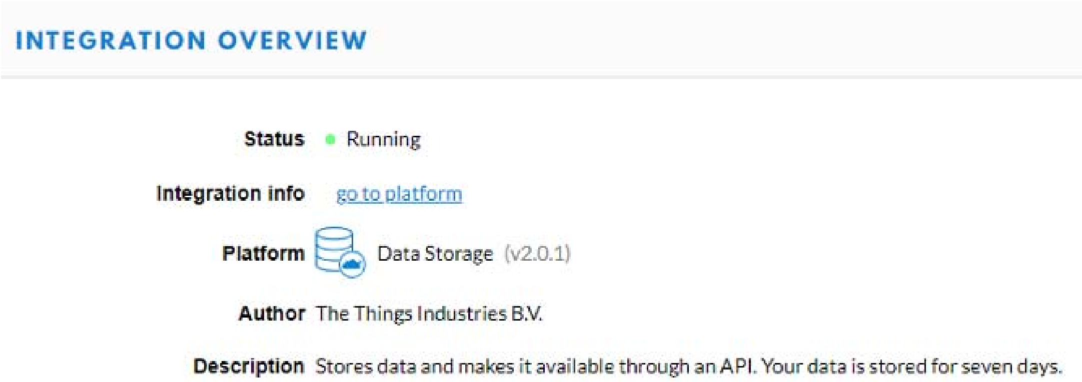

Figure 57: Integration of http service in TTN

To find out about the API available to extract data, click on "go to platform "to get the set of APIs, which make simple request. Now, we will generate the requests by following the API documentation available to extract the desired items.

5.6 Result and discussion

In the figure below, presented the out put of our sensor node in the serial monitor of both humidity and temperature before they get trassmitted to our server TTN through our gateway

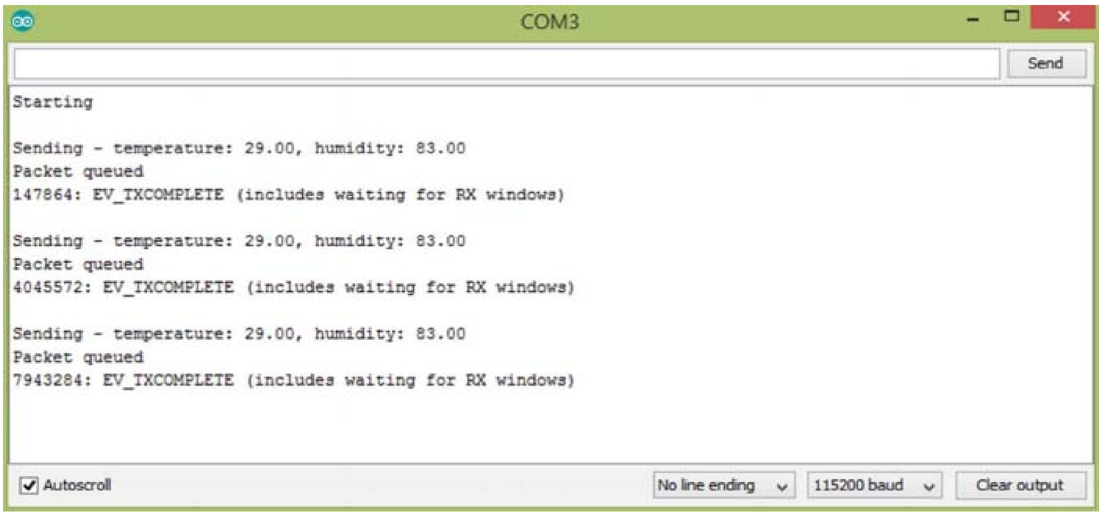

Figure 58: Serial monitor result

In Figure 69 we have the decoded payload Data as a readable string containing our values of temperature and humidity transmitted from the node to our single-channel which is an ideal low-cost solution for soil moisture monitoring system for fertigation-based production.
The node can be used to be connected to a specific spreading factor for our gateway from 6 to 12, this node is sufficient for this project especially when the strawberry greenhouses can't pass 500 m^2 while each node can reach 6 km of covering as was shown in the previous chapter.

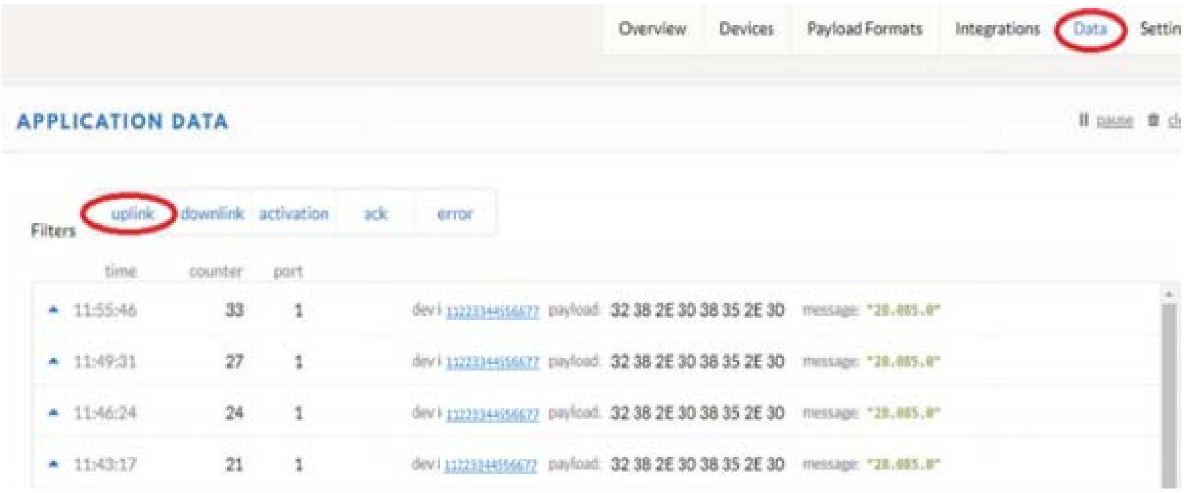

Figure 59: uplink payload

Chapter 6 Conclusion

Through this work, the issue of irrigation control for farms in remote locations was addressed in which a dynamic management of data is essential for optimal crop yield. Thus, a monitoring system for irrigation was developed which combines real-time access to information, accurate data gathering systems and great distance communication of data through the LoRa communication Protocol.

The current outcome of the solution can already be considered a viable alternative as an irrigation monitoring system which allows consulting and real-time access to information such as humidity and temperature thus allowing a single user to monitor and manage multiple remote locations from a single central command unit.

This project is still a work in progress and can still be expanded for further efficiency and autonomy, the most efficient way is the introduction of an energy independence module represented by a solar panel that would rotate following the time of day and recharge the battery for sustainability in remote locations. The second possible upgrade to this project comes from the bidirectional property of the LoRa protocol which allows the user to not only monitor the data gathered by the sensors but also give commands for certain actions to occur within the system.

In conclusion, we have made through this project the first step into the world of IoT in a comprehensive approach that combines data acquisition, electronics, embedded systems, and communication protocols. We have also tried to address some socio-economic and environmental challenges such as water conservation in irrigation systems for small and middle-scale farmers.

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