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Master thesis

Development of a Low-Power Long-Range Open Node for Agrometeorological Wireless Sensor Network

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Master thesis

Development of a Low-Power Long-Range Open Node for Agrometeorological Wireless Sensor Network

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Abstract

The thesis offers a contribution to the iXemWine project, which aims to create an innovative platform for vineyard farming. The goal of the project is represented by a radical transformation of traditional weather monitoring, towards a pervasive, ubiquitous, continuous, real-time and universal access to micro-meteorological analyses, based on a low-cost digital divide disruption in the countryside. The iXemWine paradigm is based on the creation of an open-access, long distance wireless sensor network made of easily accessible plug-and-play nodes .

The work of the thesis will be focused on the development of the end-device, in particular the power management unit, both from the hardware and software points of view.

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1 Introduction

1.1 iXem Labs

iXem Labs [1] is a laboratory of Politecnico di Torino, established in 2004 by Daniele Trinchero, Riccardo Stefanelli and Ludwig dei Ghermanti. During the past years we conducted research projects, aimed to the development of radio systems to overcome the digital divide, to improve the efficiency of productive methods facilitating sustainability processes.

Figure 1.1.1: iXem Labs Official Logo

One of the main goal that the laboratory aim to achieve thanks to their research activity is the reduction of the digital divide, especially in the rural area where the technological innovation struggle to arrive quickly due to the low economic interest of large companies. For these reason, the activity of the researchers have been focused for years in low-cost technology that can provide internet connectivity in those rural area not served by the commercial internet service provider. In the last year, another branch of research is dedicated to the emerging technology in the Internet of Things (IoT) with the same passion and purpose that have characterized the work of the iXem Labs. In this last topic, the researchers are involved in project about the development of wireless sensor network with wide range and low cost.

To date, the active research projects are:

- Senza Fii Senza Confini
- Me-Ri
- iXemWine

1.1.1 Senza Fii Senza Confini

Senza Fili Senza Confini [2] is an association of social promotion registered ad Internet Service Provider at the Ministry of Economic Development. The purpose of the association is to provide broadband connection in the peripheral and rural area where the digital-divide is still difficult to overcome. Senza Fili Senza Confini also organize free training courses to lear how to use the personal computer and how navigate in internet securely. It's the first no-profit internet service provider registered in Italy and it established the widest network owned by a University institution in the world.

1.1.2 Me-Ri

Me-RI stands for **Metering Remote Interpreter**. The aim is to use the most modern IoT communication protocols to overcome the problem of the reduced coverage range of the WM-Bus protocol used in meter reading systems. This project would like to develop a device capable to capture the readings becoming from a large number of different meters and, thanks to a wide wireless sensor network, forward them directly to the server of the service provider.

1.1.3 iXemWIne

iXemWine [3] is the first free and shared agrometeorological platform for precision agriculture. The goal of this project is to is to stimulate the use of technology in the vineyard, through the simplification of the infrastructures, the rationalization of the complexity of the devices and the minimization of the activities requested from the producer. My thesis would like to be a contribution to the development of this project, in particular, with the development of a low-power device that can interface with different types of sensors, acquiring the necessary data and transmitting them via a radio protocol to the server where they will be analyzed.

Part I

LP-WAN

2 LP-WAN Overview

Low-Power Wide Area Network or in brief LP-WAN is a paradigm that include different types of technologies that have the common goal to create a wireless are network with a wide coverage in order to interconnects battery powered devices. The typical architecture of this types of network is showed in the figure 2.0.1:

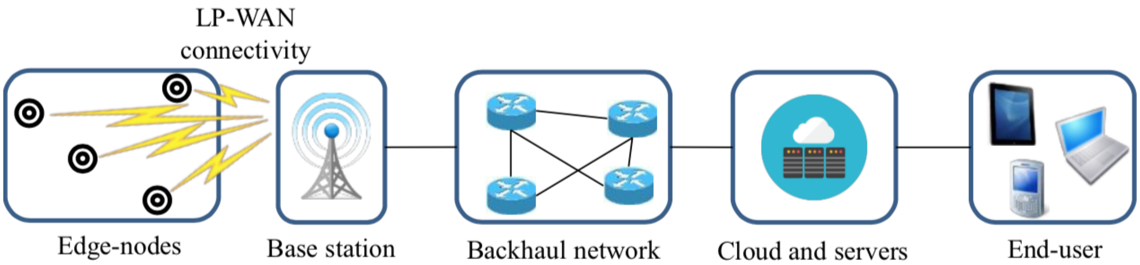

Figure 2.0.1: LP-WAN Standard architecture [4]

The network structure is similar to the cellular networks, a series of base stations provides the radio coverage necessary to provide connection between the edge-nodes to the backhaul network and then to the cloud services where data are stored and eventually analyzed. Finally, the end user could access to the data whenever and wherever he wants directly from PC, Smartphone or other internet connected devices. LP-WAN adopts a star topology network the nodes can't talk each other and no repeaters are needed, they can only connect to the base stations. This simplify a lot the network complexity. The base station and the backhaul can be realized directly by the developer to cover the interested area or can also be public provided by a service provider. This last solution can be very interesting because it relieves the user from the needing of deploy and maintain the acquisition data network. Most of the communication protocols that are part of this paradigm use ISM (Industrial, Scientific and Medical) frequency bands that are free of charge. In order to reduce the power consumption, the communication protocol are more focused on the uplink collection which has the function of transmit the information from the edge-nodes to the server. So, the downlink in limited because of the small listening windows allowed. This choice is made so as to allow the micro controller to be in low power mode the most of the time. The solution is optimal for sensing node, because they have to send data and only sometimes receive but in not suitable for actuators, however some strategies can be adopted to stem the problem.

In brief, the main features introduced by the LP-WAN network can be summarized as below:

- Long communication range
- High scalability
- Energy efficient communication protocols
- Low power consumption of the edge nodes
- Low cost of maintenance both for the edge nodes due to the fact that they don't need a SIM card and both for the network because it's possible to adopt public network

The drawbacks of the LP-WAN is the limited data rate that could not permit to exchange data too heavy like multimedia ones, for example photos also with a low definitions. This is done in order to save much energy as possible and to get a very noise-resistant signal. However, since we are talking about of network of sensors that have to transmit readings of different parameters, alert or commands, the data rate provided by this technology is more than sufficient for a lot of applications.

3 LoRaWAN

Figure 3.0.1: LoRaWAN logo

LoRaWAN specification is a LP-WAN protocol designed to wirelessly connect battery operated 'things' to the internet in regional, national or global networks, and targets key Internet of Things (IoT) requirements such as bi-directional communication, end-to-end security, mobility and localization services.[6]

This protocol is standardized by the LoRa Alliance that involved a lot of companies all aound the workd working togheter to develop and promote the protocol. This technology is based in the LoRa physical layer.

3.1 LoRa

LoRa (acronym of Long Range) is a wireless communication protocol in ISM bands, especially in the 169MHz, 433MHz and 868MHz (EU Regions) or 915MHz (USA Region) bands. It was develop for IoT and M2M applications in particular to allow long range communications and low power consumption. The LoRa physical layer is based on a Chip Spread Spectrum (CSS) modulation.[7]

Chirp is the acronym of Compressed High Intensity Radar Pulse, it's a signal that have a frequency that both increase or decrease with time. It's common in radar application. The Chirp Spread Spectrum technique is based on the Chirp signal that have constant amplitude and pass the whole bandwidth in a linear or non-linear way from one end to the other end in a certain time. This type of modulation uses all the available bandwidth to transmit the signal. There are two types of chirp:

- Up-Chirp: if the frequency passes from the lowest to the highest value
- Down-Chirp: if the frequency passes from the highest to the lowest value

Adopting this special type of signal, the CSS technique can obtain good results in very large distances and, furthermore, it's resistant to the Doppler Shift and so it can also be suitable for application in which the edge nodes are in motions.

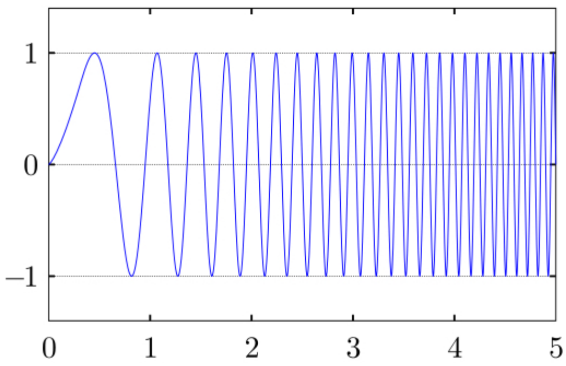

Figure 3.1.1: Example of an Up Chirp

Another important parameters of the LoRa modulation is the Spreading Factor (SF). By definition, it's the ratio among the frequency span between the starting and stop frequency of the chirp and the time in which it evolves. So, the same chirp can have different duration based on whether the communication requires greater robustness or greater data rates.

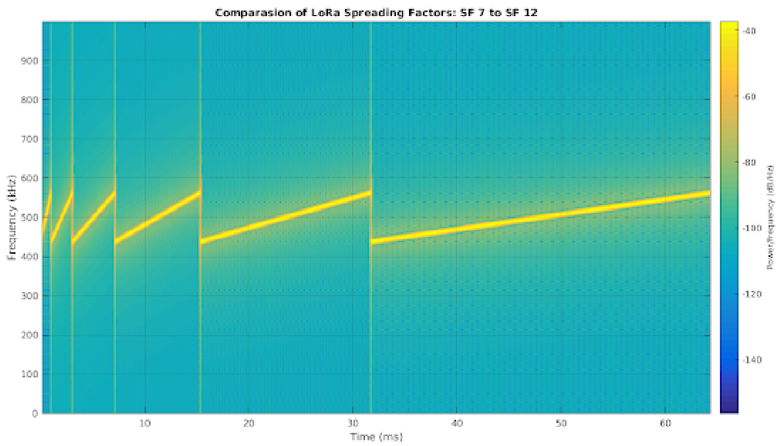

Figure 3.1.2: LoRa different Spreading Factors from SF7 to SF12

The combinations of these parameters, defines different data rates that are standardized by the LoRa Alliance and are showed more in details in the table 3.1.1.

The frame adopted by LoRa modulation is composed as follow:

- Preamble symbol - 8 bits
- Synchronization symbols - 2 bits

DR	Bandwidth	Modulation	SF	Bitrate
0	125kHz	CSS	12	290bit/s
1	125kHz	CSS	11	500bit/s
2	125kHz	CSS	10	1kbit/s
3	125kHz	CSS	9	1.8kbit/s
4	125kHz	CSS	8	3.1kbit/s
5	125kHz	CSS	7	5.5kbit/s
6	250kHz	CSS	7	11kbit/s
7	500kHz	FSK	-	50kbit/s

Table 3.1.1: LoRa standard datarates

- Physical Payload
- Optional CRC

Figure 3.1.3 shows the variation of the frequency in time of a LoRa header followed by 5 random data symbols. It's interesting to notice how the starting frequency of the up-chirp is changed in order to increase the number of available symbol in a simple manner.

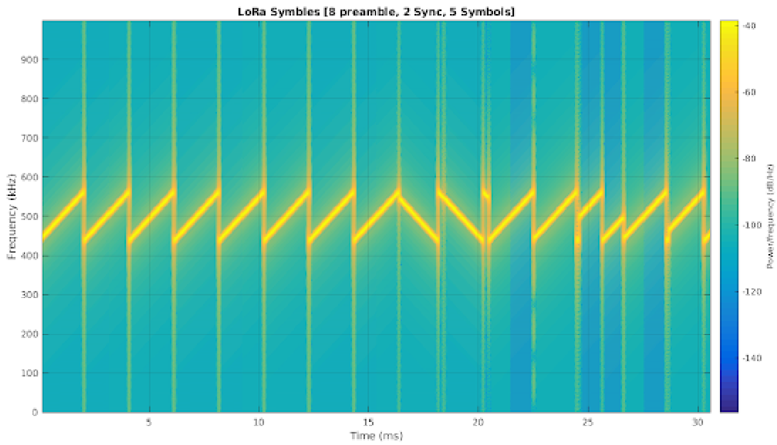

Figure 3.1.3: LoRa Symbols: Preamble, Sync and 5 Random Symbols

Semtech developed the radio interfaces in order to enable extremely low signal level reception so as to allow that even low power transmission can be received ad long distances.

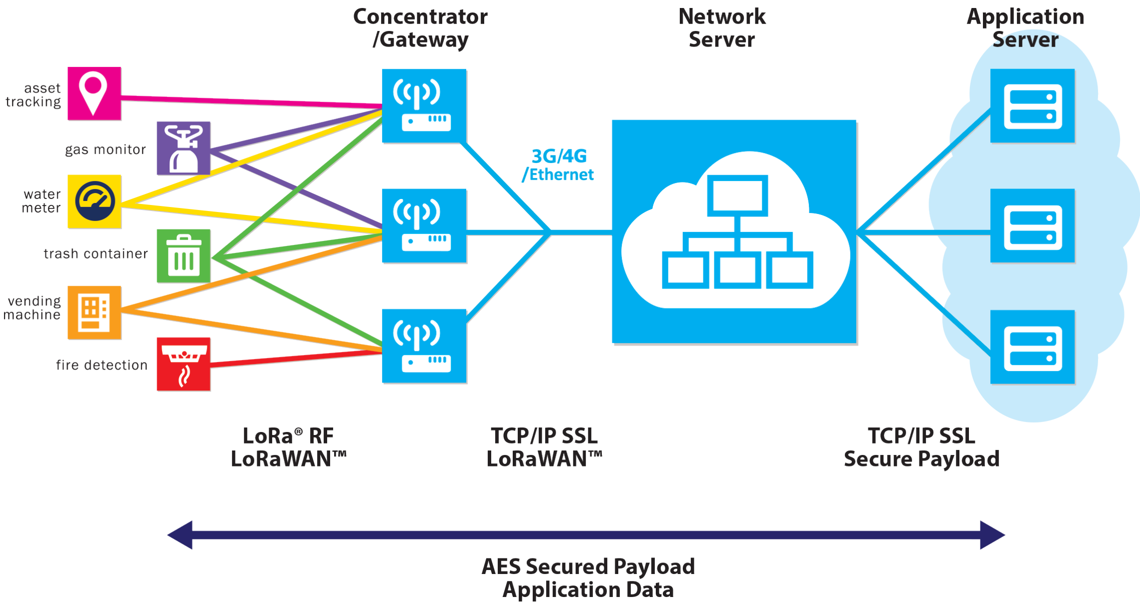

Figure 3.2.1: Standard LoRaWAN network architecture [8]

3.2 LoRaWAN network architecture

The architecture adopted by the LoRaWAN network is showed in figure 3.2.1 and, of course, is very similar to a general architecture of a LP-WAN. The end-node are connected to a series of gateway through a LoRa wireless communication using a star-network topology. The data transmitted by a single device can be captured also by more than one gateways. This is an important features because create a redundant data acquisition network that can work correctly also in case of failures of one of the gateways. A concentrator is then connected to internet in order to be able to forward all the data received to the network server of the service provider. The latter can collect the all the data and then reply to request of the different applications server that finally brings the data to collect and/or analyze them for the final users. As it's possible to notice by the figure 3.2.1, there are different types of devices and multiple application server but the LoRa network and the network server are only one. These means that these topology is well suited to be managed by a service provider and it can be a very useful advantages for the developer because he can concentrate only on the develop of the end node and the application server. The apparatuses inside the LoRa network are linked throughout a simple star-network, where the end-devices are connected to a central gateway which collects the transactions and communicate them to the network provider.
The directives for the physical and networking layer will be listed in a following

sections. In the following, the single actors of the network are analyzed more in details:

- **End Node**: it can be of two types: sensor, if its purpose is to collect data connected to it, or actuator, if its purpose is to receive commands remotely and perform predetermined actions. It is connected to the gateway by means of a LoRa communication. It's the actor that always start the conversation and do not need an acknowledge to proceed. In LoRaWAN there a three different classes of end-node that are standardized by the LoRa Alliance, they are explained in the next section.

- **Gateway**: This device is responsible for the correct acquisition or transmission of the data. It manages different communication protocol. Of course, the LoRa network, not only to acquire or send information but also to manage the join of end nodes to the network or send parameters for the end node configuration for example. Then it has to manage at least an internet connection in order to be able to connect to the network server. Since this connections is established via a standard IP connection, the gateway can be connected bot to public or private network. Each gateways can answer to a single node at a time and only after it has received a packet and inside a predefined time otherwise the end node is not listening because it is in a low power status. Theoretically, a single network can manage up to 250'000 end nodes.

- **Network server**: The LoRaWAN network server is the core of the system. It has to manages the entire network, forwarding to the gateways information about if a sensor can join or not to the network or tell to the end node if can use a higher data rates because the signal strenght is god for example. Furthemore, it has to eliminate duplicate packet that can arise by different gateway. Obviously, it has to keep available the data for the applications server.

- **Application server**: This is the server that uses the information collected by the sensors or tells to the actuator which kind of operations have to perform. It's a proprietary solutions and can interact with the network server by means of a lot of different protocol and methods developed ad-hoc.

3.2.1 Classification of end nodes

The classifications of the end node is based on the power consumption of the node. The three classes are:

Class A This is the basic class that have to be supported by all end devices that are compliant with the LoRaWAN specifications. The communication is managed according to the ALOHA protocol: the conversation is always initiated by the class A device and is asynchronous: an uplink can be sent at any time and it's followed by two downlink windows in order to give the possibility to the gateway to send some information to the node. When the device is not transmitting or receiving, it id able to enter in a low-power mode in order to save as much power as possible. It wakes up periodically after a period predetermined by the application. Thanks to these features, the class A are those devices that can work only with batteries without any kind of energy harvesting.

Class B It's similar to the previous class A but in this case the device is synchronized with the network server by periodical beacons and open downlink slot at scheduled times. In this way, the device is able to acquire downlink with a predetermined time with a latency smaller than before. The smallest interval that can be used is 128 seconds that can suits a lot of different applications. Of course, these type of managing consume more power than before but however the battery supply still valid. This category includes all those battery powered devices with an energy harvester.

Class C This classes is related to low latency devices. In this case, the end node is still in receiving mode all times. So, the network server can initiate a communications sending a downlink at any times. The drawbacks os the high energy consumption of the device that, in this case, need continuous power supply to work correctly. Since all devices need to be compliant with class A, also a battery powered devices can be temporarily switch to a class C only when needed. In this category there all the powered sensors and the actuators.

Part II

iXemWine

4 Innovation and Agriculture

The modern agriculture is characterized by a development common to other industrial production process: it benefits from the emerging technologies in order to introduce better precision and to optimize the resources. An interesting aspect is that unlike the manufacturing and tertiary sectors, the application of modern technologies don't introduce only the production mechanization or the standardization of the final product but they are also focused on a greater mastery of cultivation practices. The knowledge of the biological, chemical and physics necessity of plants and soil, finds its increasing importance in reaching an ever greater sustainability in order to guarantee the highest naturalness of the food. In this stimulating context, the precision agriculture represents the implementation of a set of agricultural methodologies technologically advanced. The mechatronics and robotics contributes to this evolution with autonomous driving tractors and tools for selective application and dosage for an increasing effectiveness of the treatments. The computer and telecommunications engineering contributes with new highly advanced devices capable to collect and transmit data through sensor to allow the possibility to easily realize a system for remote sensing, in particular we can talk about what is called the Internet of Things (IoT), that increase significantly the extensiveness and the availability of the knowledge. As a consequence, technology generates a lot of useful information to better understand the phenomena that occurs during the growing and so help in the planning and management of the standard operation but also more for contrasting the emergency situation. The data collection is supported by even smaller and energy efficient sensor, by drones and satellites with cost that becomes more sustainable from year to year. A further improvement not do underestimate, it's the possibility to store all the information on cloud services and then to elaborate them using advanced simulation tools and algorithms that in many case can work in an autonomously in order to directly providing real-time notification in case of potentially harmful situation.

4.1 Agrometeorological Data

It's been a long time since agrometeorology is the most effective tool for planning phytosanitary control and preventing damage caused by climate change. The knowledge of the weather data related to the environment and to specific parameters of the plants permits to compute micro-climatic weather forecast fundamental to prevent the onset of diseases and infectious agents with sufficient time.

Once a time, the acquisition of these particular types of information was done by big static hats containing mechanical instruments that needed to be read manually. Even the analysis was carried out without the aid of the computer, the graphs were drawn by hand and the prediction algorithms, mostly empirical, were calculated only periodically with paper and pen.

Figure 4.1.1: An example of old agrometeorological hats

The next evolution step was introduce the remote connection that allowed to send the data from the sensors directly to a server where the information was collected and analysed through mathematical model. Unfortunately, the inclusion of this type of connection has some drawbacks. The first is the increased energy consumption, so the traditional weather station grows in size and complexity, so the constructors was forced to introduce autonomous energy systems like solar panel and batteries. The other problem was the digital divide facing the countryside where the mobile coverage is not always guaranteed.

The first attempt to overcome the problem of the digital divide was the dematerial-

Figure 4.1.2: An example of agrometeorological stations with solar panel

ization of the weather station introducing the possibility to connect sensors through a WiFi network instead of a wirings with cables. In this way, the central station could be positioned where the mobile connection was present and the sensors could be installed in a radius of about 500-800 meters in line of sight. Unfortunately, this types of solution increases even more the global energy consumption of the station because every sensor needed a solar panel and a batteries.

5 iXem Wine Project

The iXemWine project wants to apply the most modern communications technologies, developed for IoT application, to the agriculture in order to overcome the limits imposed by the digital divide and, in the same time, drastically reduce the energy consumption.

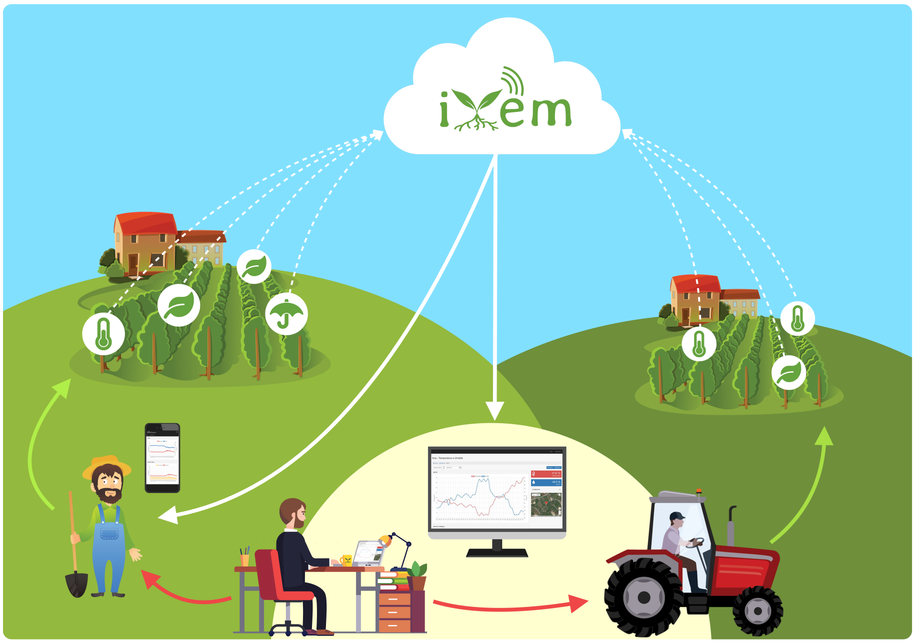

Figure 5.0.1: iXemWine Project

This is made possible thanks to the adoption of a global communication network in according to the LP-WAN paradigm. In this way, it's possible to eliminate the inconvenience of having to equip every single agrometeorological station with a SIM, which involved a high energy consumption and a high maintenance cost. Adopting this different network topology, the internet connections is needed only for the gateways. Since they can also be placed even at considerable distance from the sensors, they will be placed at considerable distance from the sensors, they will be installed in strategic locations in order to maximize the coverage and also, being outside the rural area, they will be able to take advantage of a direct power supply and a connection to internet that can be of different types (Ethernet, WiFi, Mobile) based on what is available in place. The data collected by the individual sensors will then be stored on a dedicated server that will make them available through a free and open platform.

Resuming, the main targets of the project are:

- Realize a global network for data acquisition that is widespread in the rural areas and can thus reduce the digital divide in these territories.
- Create a simple and intuitive platform that guarantees access to data in real time. It was decided to adopt a community philosophy, so all those who decide to participate in the project are willing to leave the latest data available to everyone. It is also possible to share the history a single sensors with other users in order to encourage a collaborative economy. In this way, we also want to encourage those people who are afraid of technology to approach and help each other to learn about the possibilities offered by these tools.
- Create a compact and ready-to-use device that can be installed directly in the vineyard to get a precise measure of the real environmental situations. It will have to interface with numerous sensors of different types and send the data through the coverage network. We will call this device Open-Node, it is the subject of my thesis work.

5.1 iXemWine Network

The LP-WAN protocol chosen to develop the iXemWine network was the LoRaWAN. In order to better understand the capability of the LoRa modulation in a real rural environment, some tests takes place in Monferrato lands[9][10].

For some of these tests, weather baloos are also employed to place the receiver at different height from the ground, up a maximum altitude of 100m. These particular method was used to verify the influence of the ground in the signal propagation.

The devices used for the test was a couple of development kit designed by Semtech that are equipped with a SX1272 trasceiver [11]. These kit was connected to two Arduino Uno [12] and supplied thanks to USB power banks, see figure 5.1.1.

The first test took place in Treville, province of Alessadria, adopting a mobile transmitter and a fixed receiver placed a 100m height. Thanks to this configuration, we are able to obtain the following results:

- maximum distance of 2km in a non-line-of-sight condition
- maximum distance of 40km in a line-of-sight condition

It's possible to see the RSSI [5] measurement collected in figure 5.1.2.

A second test took place in Verrua Savoia, province of Turin. In this case, the ballos was taken at a maximum height of 8 meters to simulate the roof of an house.

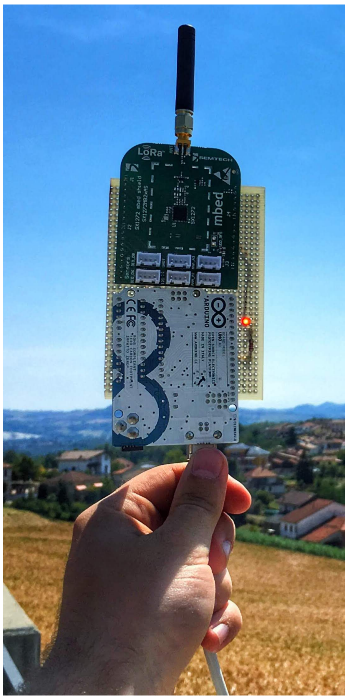

Figure 5.1.1: Arduino UNO with SX1272 development kit

In the figure 5.1.3, it's possible to see on the right the RSSI measurement obtained in Treville, while on the left, there are the measurement collected during the test in Verrua. As it's possible to notice, they are compatible.

These tests show as that the LoRa can communicate to very long range in rural area and that with only one receiver it's possible to cover an huge area. The second important result was that the height doesn't influence too much the signal propagation. This means that the gateway doesn't need to be placed at high level from the ground but it's sufficient the roof of a house, like for television antennas.

Thanks to the results obtained during these tests, the iXemWine network could born. It adopts the LoRaWAN protocol that merge the powerful LoRa modulation and the open source MAC layer. The gateways are placed in strategic positions using only existing structure like home, cellars or public buildings of institutions that have granted patronage to the project.

In order to minimize visual impact, the gateways are compact. Their dimension are comparable to an A4 paper sheet and they can also be painted. The receiver is connected to a Routerboard, in this way some enhanced features can be achieved. One is the possibility to use different types of internet based on the type of connection available, like WiFi, 3G/4G internet key or Ethernet. In some cases, more than one

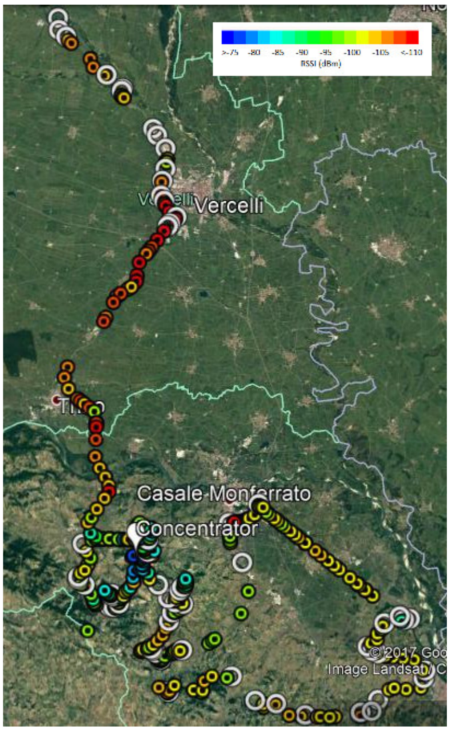

Figure 5.1.2: RSSI measurement collected during Treville test

connections can be used in parallel in order to have a redundant and more robust connection. Furthermore, the routerboard can be programmed in order to provide a remote connection, for example through a VPN. This permits to access to the gateway configuration remotely and also to perform automatic check on the status of the receiver and send a notification in case of problems.

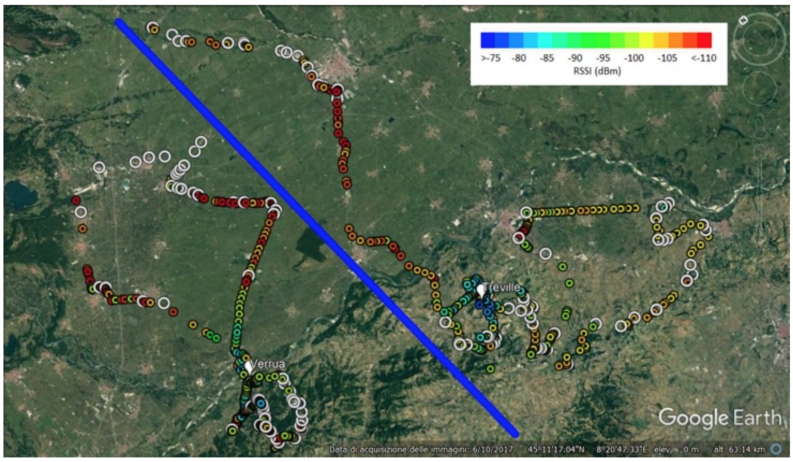

Figure 5.1.3: RSSI measurement comparison from Treville and Verrua tests

Part III

Open-Node

6 Open-Node: the idea

The Open Node is a LoRaWAN end node, developed for the iXemWine project, capable to handle different hardware configuration and be compliant with the project constraints. The device must be flexible enough in order to handle all the possible physical sensors that can be attached to it, such as temperature and humidity of the air, leaf wetness, rain gauge and many others. This imply that the board needs to be able to communicate through different serial protocols and also to handle analogical signals.

For what concerns the hardware, there are two main aspects that should be taken in consideration when developing the board. The first one is that since the device works in a LoRaWAN network, then it must be equipped on board with a transceiver that support the Lora modulation. Finally, since the device must be deployed outdoor, with no energy harvesting, the power consumption must be has lower as possible.

Following the LoRaWAN specification, it is trivial to understand that the Open Node must be a device of class A which is the most suitable for low power devices. Nevertheless this is not enough, it will be crucial to handle the power consumption of the physical sensors attached to it, since they can negatively affect the performance.

A final note must be given to the package of the board. As mentioned above, the device will be deployed in vineyards, exposed to all the weather events. The package must be designed to be IP56, using robust components and able to works on a huge range of temperature.

7 Hardware Design

The first specification to be respected is the full compatibility with the LoRaWAN protocol. From this indication comes the first constraint which is the adoption of a transmitter developed by Semtech as they are the only ones able to communicate via LoRa modulation. The module have an SPI serial communication and therefore can be combined with any processor equipped with this peripheral.

7.1 Microcontroller

The choice of the microcontroller is one of the most important because it represents the heart of the device. For this specific case, we can choose two different types of approach: the first consists in using two separate chips, one for the microcontroller and one for the transceiver. The advantage of this solution is the better flexibility in the choice of the single ones. The second option instead consists in adopting one of the chips that integrate both components inside them. In this case, the drawback is less flexibility in the choice but there is an advantage in the implementation phase because you have to deal with the correct assembly of a single component instead of of two thus redressing the possibility of error. Furthermore, with only one chip is also possible to achieve a better routing of the whole boards optimizing better the space.

The solution chosen for Open-Node is the second solution, adopting the chip CMWX1ZZABZ produced by Murata[13]. The internal structure can see in figure 7.1.1.

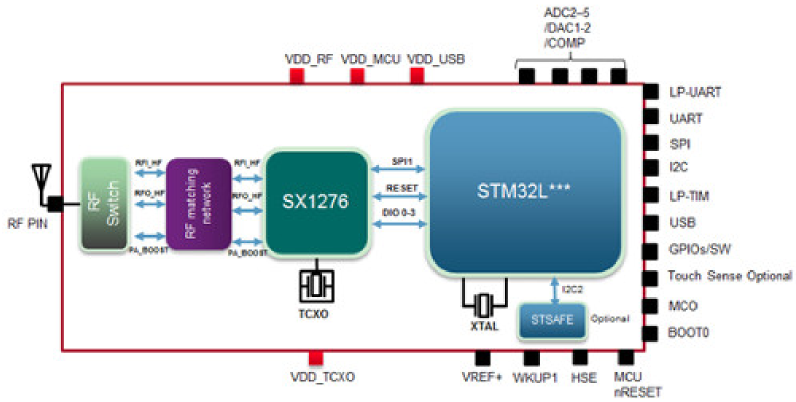

Figure 7.1.1: Murata CMWX1ZZABZ internal structure

This is a compact, low cost, low power wireless module that supports the LoRaWAN protocol. The module is quite compact and is constructed in a shielded package comprising a Semtech SX1276 transceiver and an ST Microelectronics STM32L0 series microcontroller (MCU). A TCXO with robust low drift thermal characteristics is directly integrated in the module in order to provide an accurate clock source for the RF transceiver. The module can provides communications via peripheral interfaces like UART, SPI or I2C and include also an ADC and 18 GPIOs in order to have a quite good flexibility. The chip can support a voltage supply between 2.2 and 3.6 VDC that much the possibility to supply it with batteries and can operate from -40°C to +85° so it can operate in external environment. An option STSAFE secure element can be incorporated into the MCU to enhance the network security. in the following section, the microcontroller and the transceiver are analyzed more in details.

7.1.1 ST Microelectronics STM32L0

The MCU incorporated inside the Murata chip is an ultra-low-power STM32L072xx. The architecture is a high-performance Arm Cortex M0 32-bit RISC core[14]. In the figure 7.1.2, it's possible to see the overall microcontroller structure.

For my application, the most interesting features are summerized below

- Ultra-low-power platform: microcontroller can support supply in range 1.65V to 3.6V. It have different low power mode, the best one is the Standby Mode that can achieve 0.29μA.
- Rich analog peripheral:a 12-bit ADC is available with up to 1.14Msps and 16 channels. Furthermore, there are 2 12-bit channel DACs and 2 ultra-low power comparators.
- Several peripheral communication interfaces including a USB and some USART, UART, SPI and I2C that can provide a good flexibility.
- Different types of timers, in particular it's interesting to pay attention to the 16-bit Ultra Low Power Timer that can be very useful for those application which needs a timer running continuously. This type of timer can work also when the microcontroller is in standby mode. Another important peripheral is the Real Time Clock (RTC) that is used both to calculate the time interval between two consecutive measurements and the LoRa protocol to check compliance with the specifications.

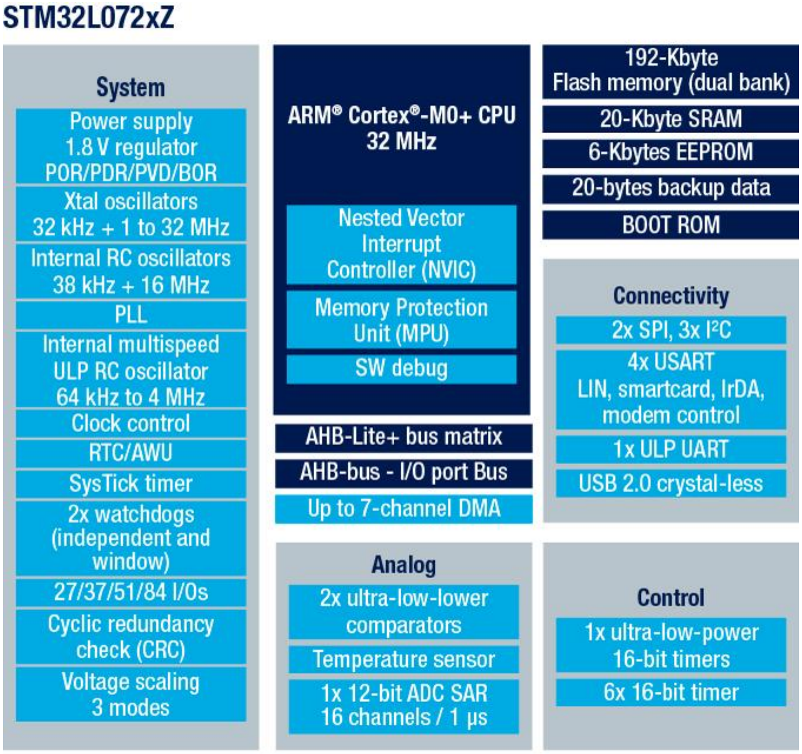

Figure 7.1.2: STM32L072xx overall structure

7.1.2 Semtech SX1276

The other important chip included inside the Murata module is the Lora Semtech transceiver SX1276[15]. It's fully compliant to the LoRa modulation and it can achieve a sensitivity of over -148dBm using low cost components. The high sensitivity combined to the integrated +20dBm power amplifier provide a maximum link budget of 168dB that make this solution suitable for the applications that require long range and robustness.

This device can also work with other type of modulaiton like, FSK,GSK, MSK, GMSK and OOK, this can be a useful feature in case there is the necessity to interface two different types of network.

The SX1276 is interfaced with the STM32 thanks to an SPI bus, a reset pin and other four GPIO pins that can be programmed to compute different task such as tell when there is a packet to receive or to know when the microcontroller wants to transmit somethings. Respect to the Semtech SX1272 used during the test presented in previus section, the transceiver included inside the Murata can reach better performance from the radio point of view and so it can achieve even better performance that those found during the test.

7.2 Evaluation Board

Before to proceed with the design, it was necessary to make some test in order to validate the choice of the Murata chip, specially from the power consumption point of view.

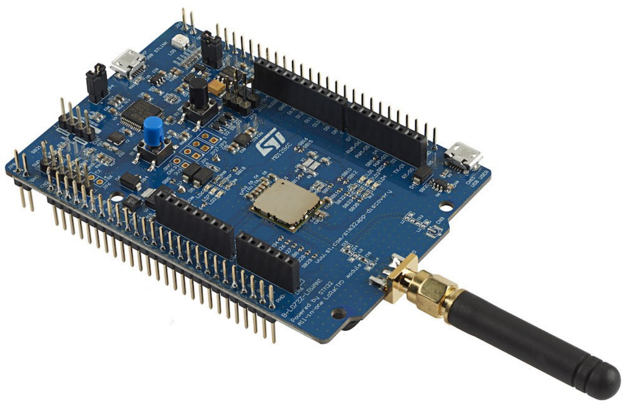

Figure 7.2.1: B-L072Z-LRWAN1 Evaluation Board

This test was made using the development kit B-L072Z-LRWAN1[16] produced by the ST Microelectronics representeed in figure 7.2.1. In addition to the chip presented above, this board has:

- On-board ST-LINK/V2-1 debugger/programmer with USB re-enumeration capability: mass storage, Virtual COM port, and debug port
- SMA and U.FL RF interface connectors
- Board power supply through the USB bus or external VIN/3.3 V supply voltage or batteries
- One user and One reset push-buttons

Together with the development board, the ST Microelectronics provides all the software expansion tool I-CUBE-LRWAN[17] that include a set of libraries and example specially created for this integrated circuit in order ot provide all the necessary tolls for the development of a custom application.

7.3 Power management

7.3.1 Power consumption tests

The first choice to make for those concern the managing the power of the board is which kind of power supply choose. In the case of the Open-Node, as required by the specifications, the power supply must be purely supplied by batteries without the aid of other sources such as, for example, solar panels. However, it remains to choose which type of battery to adopt. Before making this choice, it was necessary to carry out tests to have a real estimate of the consumption of the chip, both during standby that during transmission of the data.

Some useful data are obtained thanks to the test performed in laboratory:

- Standby mode current: $I_{Stb} = 460nA$
- Maximum current during transmission: $I_{TX} = 38mA$

In order to calculate an average consumption of the development kit, the so called Packet Air time, the time needed to send a packet of information, is needed. It's possible to retrieve this value using the LoRA calculator online tool[18].

Figure ?? shows the used parameter for computing the Air Time.

The obtained transmission time is Transmission time: $t_{single\_TX} = 1318ms$.

Since that for the iXemWine project the Open Node will have to make and transmit a measurement every 10 minutes, in an hour the device is in transmission mode for $t_{TX\_hour} = 8s$ while it is remains in Standby mode for $t_{Stb\_hour} = 3592s$.

At this point, the average current over an hour can be calculated:

$$I_{Average} = (I_{Stb} * t_{Stb\_hour} + I_{TX} * t_{TX\_hour})/3600s = 0.085mA$$

7.3.2 Batteries

The Open Node wants to be an easy to use plug and play tool, which requires the least number of possible maintenance operations. This also because it will be installed, during use, in vineyards that are not always quickly reachable by the owner. Therefore, from one hand the duration of the batteries must be sufficiently long so as not to have to force the winemaker to intervene too soon to replace it. On the other hand, we must also try to guarantee a simple and intuitive replacement of exhausted batteries. This suggests the use commercial batteries if possible because

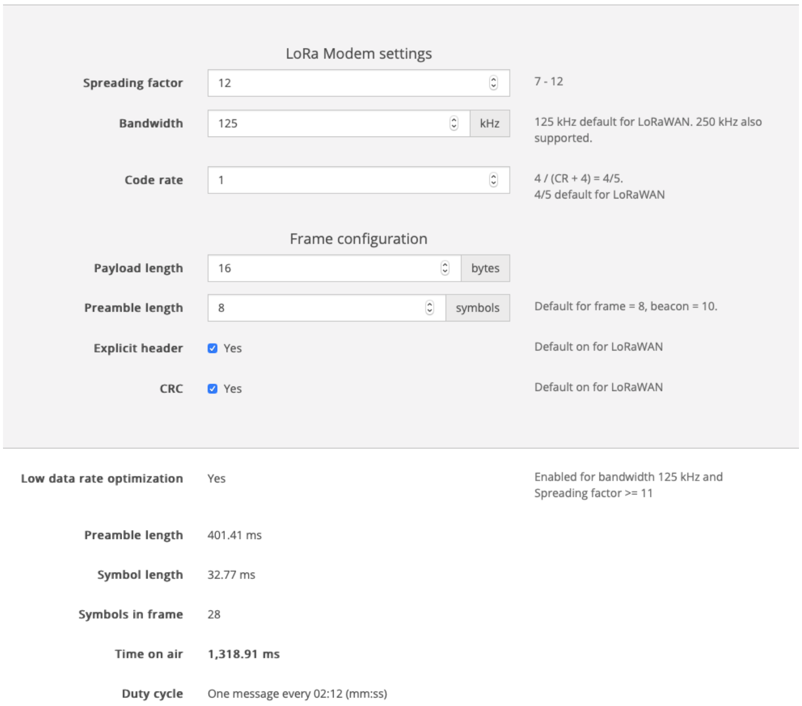

Figure 7.3.1: Air Time computing using Lora Calculator Tool

are easily available on the market. Given these conditions, the first choice fell on the simplest AA-type alkaline batteries that are sufficiently compact and, above all, easily available. This type of battery can have a maximum capacity of $2600mAh$[19]. So, the expected duration of an Open-node can be calculated as:

$$Open\ node\ duration = I_{battery}/I_{Average} = 30.623\ hours$$
$$= 3\ years\ and\ 208\ days$$

Starting from the result obtained during the power consuming test, we can calculate an expected duration reachable with this type of batteries that is equal to 3 years and 208 days. It's simple to see that this result also satisfy the the first request on a sufficient life time and makes this the appropriate option for the Open-node. Obviously, it can be possible to reach longest duration with the use of special purpose battery like the one used for metering application for example. However, this type of solution would have caused difficulties for the user in finding this type of device and also an higher cost. The alkaline batteries have a nominal voltage of 1.5 Volts that is too small to be compliant with the range requested by the Murata chip. The solution, fortunately, is simple because is sufficient to use a series of two AA batteries to have a nominal voltage of 3V that suit the characteristic requested by the microcontroller.

7.3.3 DC-DC Step Up converter

One of the specifications of the Open-node is to be a flexible device that can then interface with different types of sensors. However, it is not certain that all the sensors are compatible with the voltage range provided by the battery adopted. To overcome this problem, it is necessary to insert a DC-DC step-up converter which, starting from an input voltage included in the functional range of the Murata chip (2.2VDC to 3.6VDC) can supply a 5VDC output voltage. To do this, I used a device develped by Microchip: the MCP16251[20] that is a compact, high-efficiency, fixed frequency, synchronous step-up DC-DC converter. This family of devices provides an easy-to-use power supply solution for applications powered by either one-cell, two-cell or three-cell alkaline, NiCd, NiMH, one-cell Li-Ion or Li-Polymer batteries. Low-voltage technology allows the regulator to start-up without high inrush current or output voltage overshoot from a low-voltage input. High efficiency is accomplished by integrating the low-resistance N-Channel boost switch and synchronous P-Channel switch. All compensation and protection circuitry are integrated to minimize external components. MCP16251 operates and consumes less than 14μA from battery after start-up, while operating at no load (test condition: VOUT = 3.3V, VIN = 1.5V). The devices provide a true disconnect from input to output while in shutdown and it consumes less than 0.6μA from battery. This fact permits to the Open Node to completely shut down the sensors working at 5VDC in order to same power.

The typical application circuit is showed in figure 7.3.2

7.3.4 High Side switch

Other sensors instead are compatible with the voltage supplied by the batteries and can therefore be powered directly by them. Even in this case, however, it may be useful to switch off the sensors to ensure that the Open-node can save energy when it is not measuring. This possibility can be achieved by using two different approaches: the first is to use a low-side switch that is simpler to implement as it requires fewer components, the second consists in creating a high-side switch which is more complicated but may be more useful in some cases. In the case of sensors whose information is supplied through a resistance variation, this variation must be converted into a voltage using a voltage divider. To ensure that the current flows inside the divider only when it is necessary to make the measurement, it is necessary

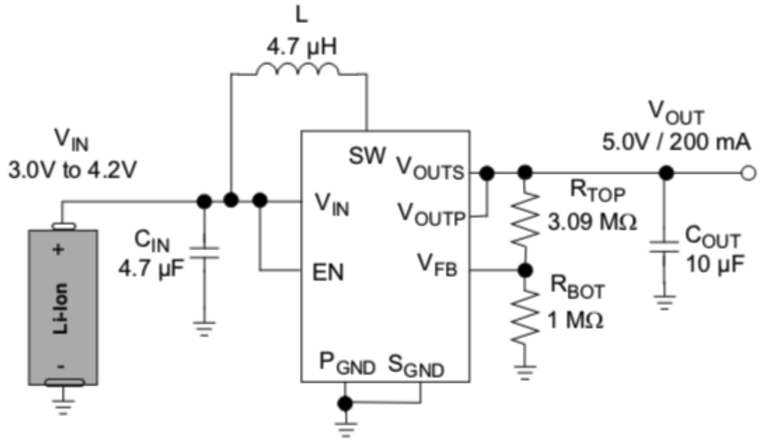

Figure 7.3.2: Microchip MCP16251 typical application schematic

to insert a switch in order to be able to power off the sensor. If you insert a low side, you need to make a Ground connector (GND) for each sensor and therefore more space is needed on the board. Furthermore, in the case of devices that have a digital component and communicate via a serial protocol, the low-side switch is not a suitable solution as it does not guarantee to completely turn off the device. This happens because this type of approach only disconnects the Ground (GND) which is the reference potential, leaving the others connected. The device thus finds itself with a virtual GND that can still flow current and therefore consume energy. The solution that adopts the high-side switch is therefore the most flexible even if the implementation can be more complex. To get the best performance from an energy point of view also for this design phase, I decided to adopt the component of the TPS222860DBVR by Texas Instruments[21]. It's s a small, ultra-low leakage current, single channel load switch. The device requires a VBIAS voltage and can operate over an input voltage range of 0 V to VBIAS. It can support a maximum continuous current of 200 mA. The switch is controlled by an on/off input (ON), which is capable of interfacing directly with low-voltage control signals. The VBIAS range is between 1.65V and 5.5V that matches the voltage provided by the alchaline batteries. It has a leakage voltage on Vin of 2nA and a leakage voltage on VBIAS that is at maximum 10nA (with VBIAS=5.5V). This current consumption can be neglected because doesn't influences the overall power consumption also in stand-by mode. In the figure 7.3.3, the most common application schematic is showed.

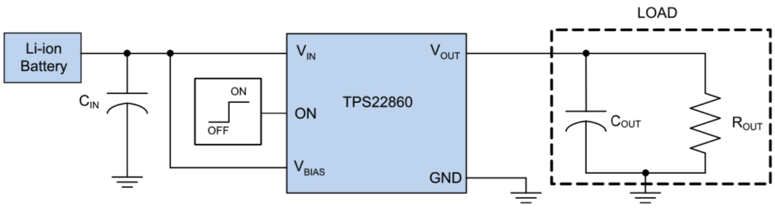

Figure 7.3.3: Texas Instruments TPS22860DBVR typical application schematic

7.4 Antenna

Since the Open-node is required to be a Long-Range communication device, the choice of the antenna is an important parameter in the design. On the market, there are a lot of different types of antenna that are designed to work in the 868MHz bands. So, taking a look to the specification given for the Open-node, it can be seen that:

- Since the Open-node has to be installed in a rural environment, specially directly inside a vineyard, it must have a compact size or maybe it can be integrated directly on the PCB inside the enclosure.
- The Open-node want to be a simple plug-and-play device that can be installed directly by the end user. So, the best choice is an antenna which can be installed also by a non expert user, therefore the antenna must not require special pointing operation towards the gateway.
- The iXemWine network could provide a redundant coverage in order to increase the robustness of the system, so, the best choice could be an antenna that is as omni-directional as possible.
- The device under development has to be able to communicate over long distance. To do this, only the LoRa modulation is not sufficient, also a correct antenna that not limit the signal strength has to be adopted.

Looking at these considerations, the choice to include the antenna directly on board has to be discarded due to the fact that the ceramic antennas have not sufficient performance both from the point of view of the gain that from the omni-directional characteristics. Similar conclusion can be achieved also for the patch antennas, in this case the gain is better than before but also these types have a directional radiation pattern. So, a better solution can be to use an out of the board antenna and, therefore, first it's necessary choose which kind of connector to use. The choice that I have performed is to adopt a SMA connector because it could provide good mechanical robustness and have a compact form. Furthermore, I decide to connect it directly on the board. This solution was adopted in order to simplify at the best the board and to avoid a pigtail connected on the board with an UFL connector because this last is more delicate. It can be ruined if badly connected and can be detached due to shock or vibration.

On the market, there are different type of antenna suitable for the bandwidth used by LoRa and with this type of connector. For this application, it's necessary to have a compact antenna so the final choice was to use a compressed whip antenna, in particular the LPRS ANT-SS900[22].

Figure 7.4.1: LPRS ANT-SS900

7.5 Open-Node Schematic

After the selection of the components, the next step is to draw the schematic of the board. To do this, the Eagle[24] EDA (Electronic Design Automated) software was adopted. This is a cross-platform tools created by the CADSoft Computer and than acquired by the Autodesk. It permits to design a whole electronics circuit, from the schematic to the PCB (Printed Circuit Board). It permits also to performs Spice simulation and it have a great integration with other tools developed by the Autodesk in order to create custom enclosure and so on. This software is constantly evolving and therefore new functions are added very often. For example, now it's also possible to set up and run auto-routing procedure.

The resulting schematic is showed in figure 7.5.1, figure 7.5.2, figure 7.5.3 and figure 7.5.4.

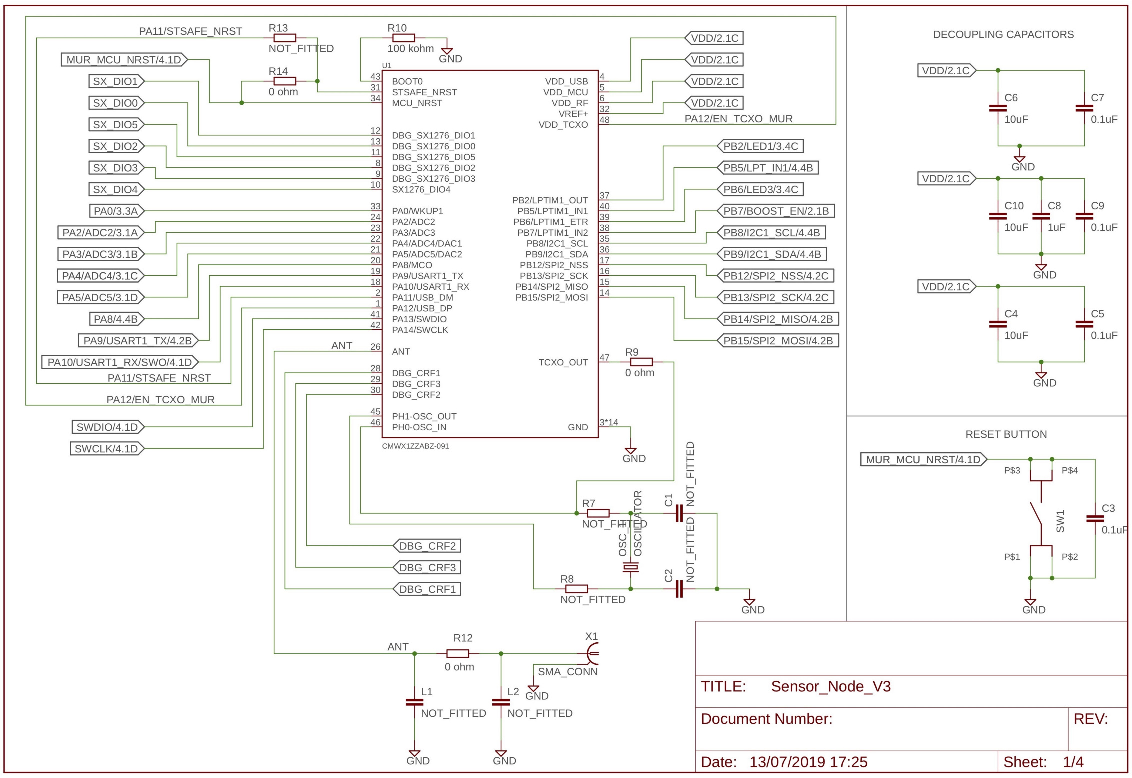

Figure 7.5.1: Open-Node Schematic: Page 1

First page shows how the Murata chip is connected. Following the specification in the datasheet, some capacitor are added on the supply voltage line in order to guarantee a stable voltage. I added also the possibility to use an external oscillator, these is a solution for future improvements. Particular attention must be given to the lines that connect the RF output of the chip to the antenna. I added the possibility to insert a PI filter made by two capacitors and a inductor. The filter is useful to correctly adapt the lines and to filter the spurious emission that could occurs . At the moment the filter is not inserted on the board and so the inductor is substituted with a 0Ω resistor.

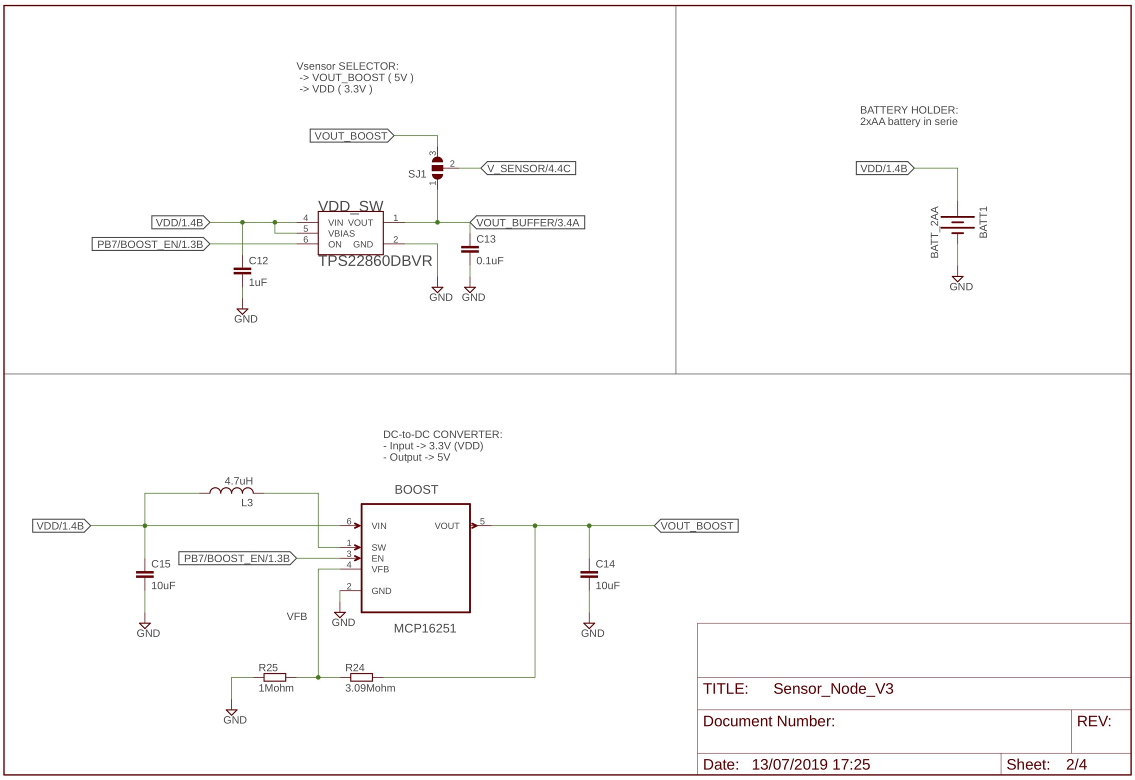

Figure 7.5.2: Open-Node Schematic: Page 2

In the second page, there are the schematics to the power management. So, it is possible to notice the battery that provides the VDD, the circuit for the Step-Up converter and the one for the High-side switch. It has also been inserted a selector to permit the choice to supply the attached sensor (through V_sensor) with the output of the converter (5VDC) or with the output of the switch (VDD).

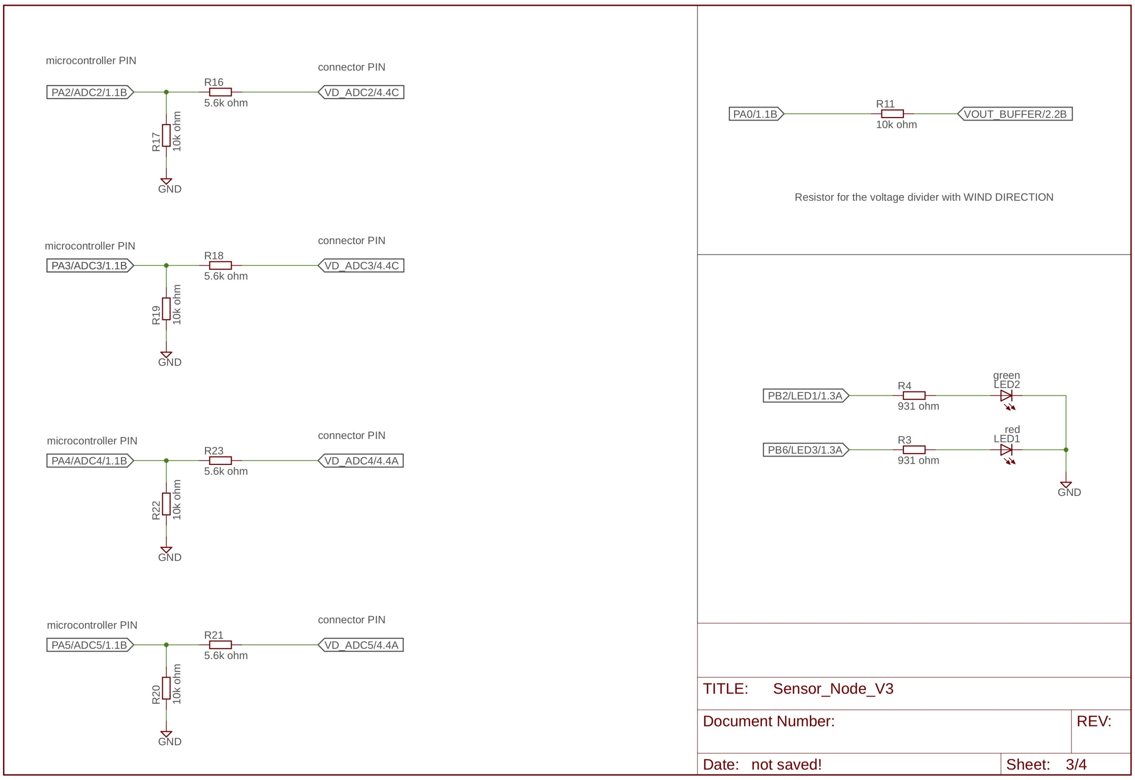

Figure 7.5.3: Open-Node Schematic: Page 3

The third page is interesting because shows the input and output signal management. Two LED are inserted in order to notify the user when the board is active, if it have join the iXemWine network and when it are sending a message. In order to not waste energy, these LEDs can be enable or disable remotely. The resistor R11 is needed to make the wind direction sensor working correctly. Since it is a variable resistor sensor, another resistor is used to create a voltage divider and so to be able to convert the resistor variation into a voltage variation readable through an ADC. The last things presented in this page are the voltage divider connected through the analogical input line of the board and the ADC inputs of the microcontroller. This is to limit the maximum input voltage to the ADC of the microcontroller. It should be noted that the Murata chip is powered directly by the batteries, so its power supply voltage decreases as batteries are discharged. To prevent this from affecting the ADC's operating range, Vref was chosen as its full scale value. It is created internally by the microcontroller and it has a constant value of 1.65V. For this reason it is necessary to limit the input voltage to the ADC to a value lower than Vref by means of voltage dividers. In order for this operation to be negligible from the point of view of the error introduced, a 1% tolerance resistance was used.

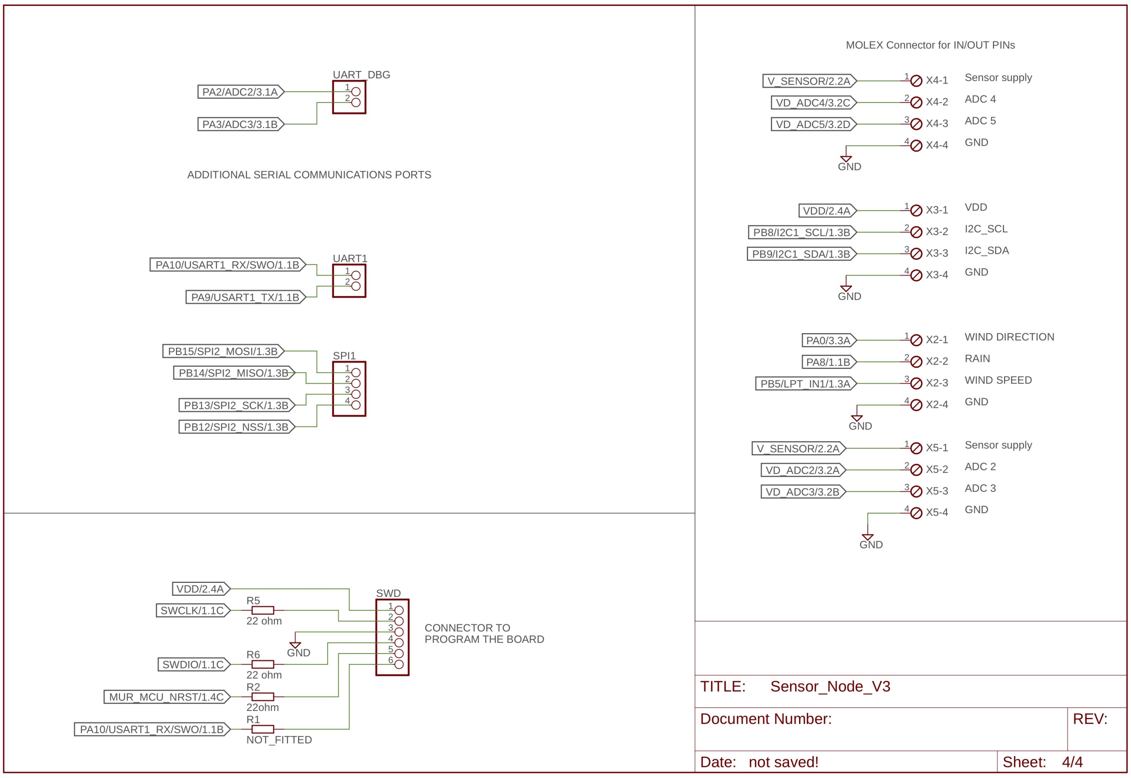

Figure 7.5.4: Open-Node Schematic: Page 4

The last page simply shows the connector used to connect the sensor as well as the necessary connector for software programming and debug.

7.6 Printed Circuit Board

The last step before to produce and assemble the board is the designing of the PCB (Printed Circuit Board). The board production process will be performed by PCBWay[25], while as regards the assembly of the components, it will be carried out inside the laboratory. The Open-node will be a 4-layer PCB so it's possible to take a look to the characteristic provided by the manufacturer:

- Board Size Tolerance: ±0.2mm/±0.5mm
- Board Thickness: 0.4-2.4mm (10%)
- Minimum Trace Width and spacing: 0.1mm/4mil
- Drill Sizes (CNC): 0.2-6.3mm
- Minimum Character Width x Height(Legend): 0.15mm x 0.8mm

Thickness	Copper thick	Laminated chart	
1.6mm±10%	1oz		Copper 1 18 um--plating to 35um Dielectric 1-2 0.11 mm dielectric constant 4.29 Copper 2 35 um Dielectric 2-3 1.13 mm dielectric constant 3.96 Copper 3 35 um Dielectric 3-4 0.11 mm dielectric constant 4.29 Copper 4 18 um--plating to 35um

Figure 7.6.1: PCBWay 4-layer stack up

In figure 7.6.1, the 4-layer stack up provided by the manufacturer is showed.

The dimension of the board are given by the chosen enclosure, the GEWISS GW44205[23], a plastic IP56 box that is suitable to work outside and can withstand the elements.

At this point the drawing of the board can start. The final result is showed in the figures 7.6.2 that shows the Top layer of the board while the figure 7.6.3 shows the bottom layer. The other two layer are dedicated entirely to the supply voltage. In particular, the layer 2 in the ground plane and the layer 3 is the power plane totally connected to VDD. The layer are placed in this order because the ground plane is needed under the RF lines, this fact will be discussed in the next subsection. Particular attention has been paid to the positioning of the chip to ensure that there is sufficient space to carry the design of the line for the radio frequency part in the best way. The goal was to get a straight line as short as possible. Furthermore, the SMA connector needed to be positioned on one of the short sides of the board, in

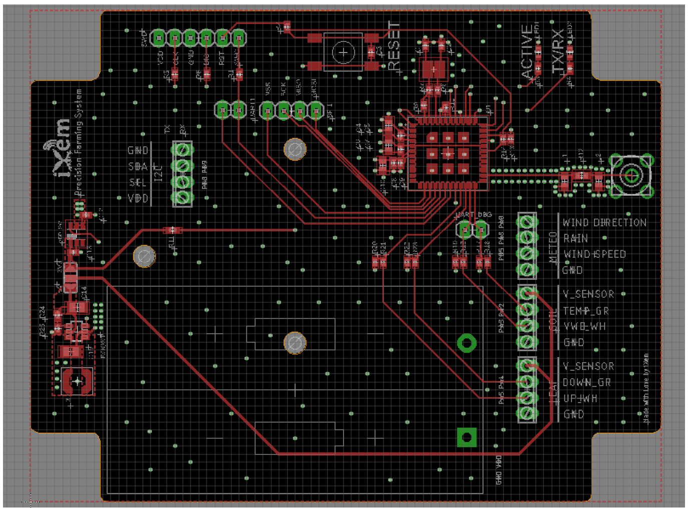

Figure 7.6.2: Open-node Top layer designing

order to simplify the subsequent assembly of the open node within the vineyards. The combination of these two constraints has generated the solution showed in the figures. During this phase it is important to follow the directives indicated by the manufacturers for the correct positioning of the components. Especially when it concerns condensers that must be positioned at certain points to best guarantee their filtering and power supply stabilization. Also the placement of the connectors is not casual but follow a precise scheme int order to facilitate the mounting and cabling operations of the Open-node. As you can notice, all the components, both SMD (Surface Mount Technology) than the Through-hole, are placed on the Top layer while on the bottom layers there are only some routes but any components. This was a precise design effort to make the welding operations of the components easier and faster because it's sufficient a single passages on the pick and place machine and then in the oven. Otherwise, if the component are placed on both the layers, a first passages is needed with an high temperature solder paste for a first layer and subsequently a second passages for the rest layer with a low temperature solder paste. It increases production time and cost. All the rules provided by PCBWay was used to set up the DRC (Design Rule Check) rules that can help, with automatic check, to find errors in the routings. Furthermore, the information provided are used to setup correctly the creation of the Gerber and the Drill files that are the files used by the producer to print the board. Eagle can also automatically generates the Bill of Material (BOM) file that can be uploaded on the electronics online store to find and buy the components in a fastest way.

The final result of the board design can be see in figure 7.6.4.

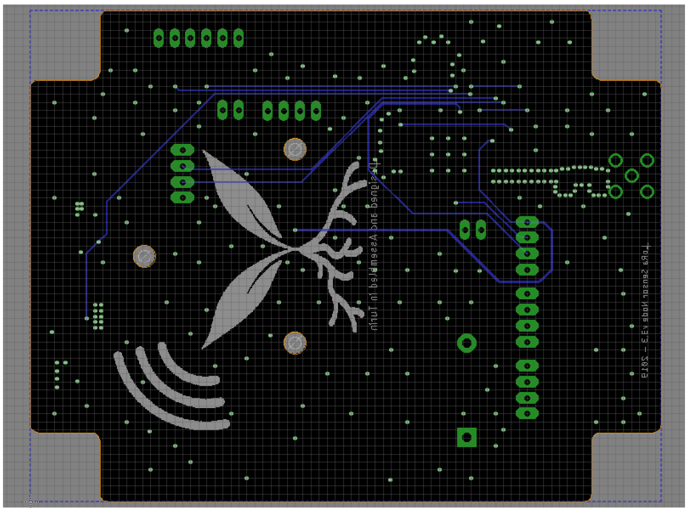

Figure 7.6.3: Open-node Bottom layer designing

7.6.1 Transmission line

The most delicate part during the PCB development was the line that connect the RF pin of the Murata chip to the SMA connector antenna because it works at high frequency and so it is a transmission line. In order to interface correctly this two components, it's necessary build this line with a characteristic impedance of 50Ω In this way, the circuit works at impedance matching conditions and so the losses due to the reflections are limited. The value of the characteristic impedance is affected by the height of the dielectric, by the value of the dielectric constant εr, that are fixed values provided by the PCB maker, and by width of the trace that is the value which can be modified to adapt the impedance.

In order to design the RF route in the bast way, the Saturn PCB Tookit[26] was used. It is a freeware resource for PCB related calculations. It incorporates many features that PCB designers and engineers are in regular need of like current capacity of a PCB trace, via current, differential pairs and much more.

In particular, the model that have to be used in this case is the Coplanar Waveguide. Figure 7.6.5 shows the structure of this type of microstrip line. Thanks to this tool, it has been obtained that the RF route must have a width equal to 0.21mm to have a characteristic impedance of 50Ω.

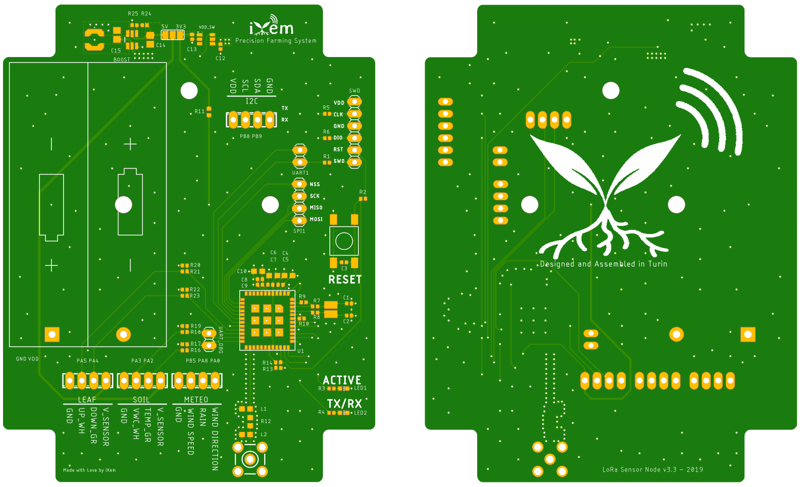

Figure 7.6.4: Open-node final designing

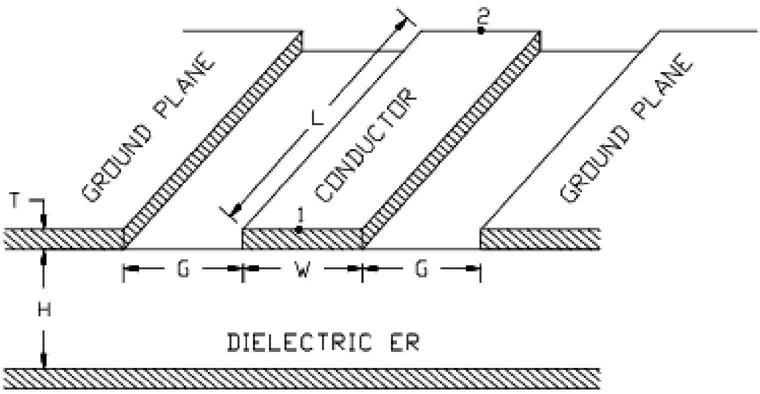

Figure 7.6.5: Coplanar Waveguide scheme

7.6.2 Assembly process

Once the board are printed and shipped to the iXem Labs, the last step to complete before to have the Open-node is the assembly of the components

Thanks to the instruments available in the Department of Electronics and Telecommunication, this process could be permed directly inside the polytechnic laboratory. The soldering process can be summarized on four main steps:

1. Place solder paste on the SMD component pads. The paste is composed of micro-ball of solder inside a flux liquid. The chemical composition may differ depending on the characteristics required. If, for example, some components cannot be subjected to too high a temperature, a low temperature paste must be used. These information can be obtained looking at the datasheet of the various component.
2. Place the component using a pick and place machine. In this case, I used a manual pick and place which, thanks to a mechanical arm, allows lifting through a small nozzle that creates the vacuum. Subsequently, through a digital camera and a monitor, it enlarges the component and allows it to be rotated and positioned on the correct pads.
3. Fuse the solder putting the board inside a special oven that permits to set up a heating curve. This last differ by time of increasing and decreasing the heat and on the maximum temperature reached. These parameter depend on which kind of solder paste is used.
4. Welding of the through hole components by using a commercial soldering iron.

At this point, the hardware designing and production of the Open-node is terminated. In the following some figures of the final results are shown.

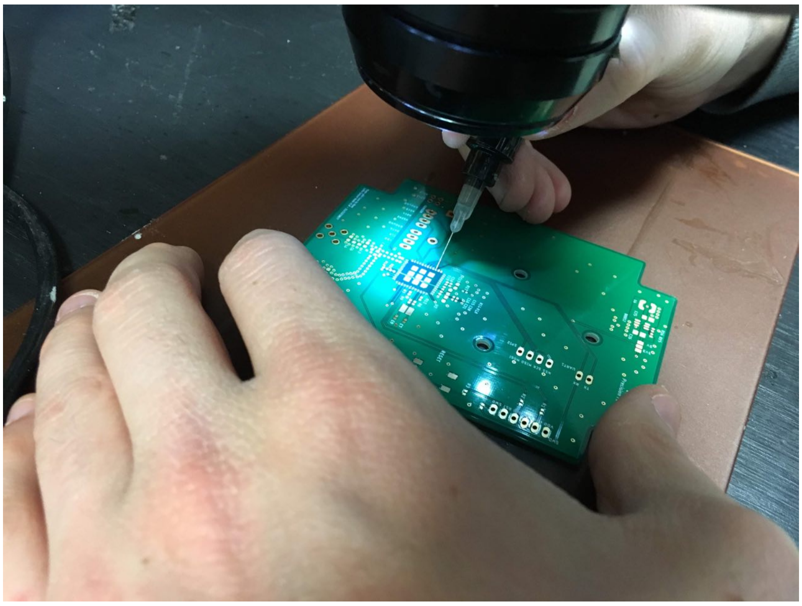

Figure 7.6.6: Solder paste placing

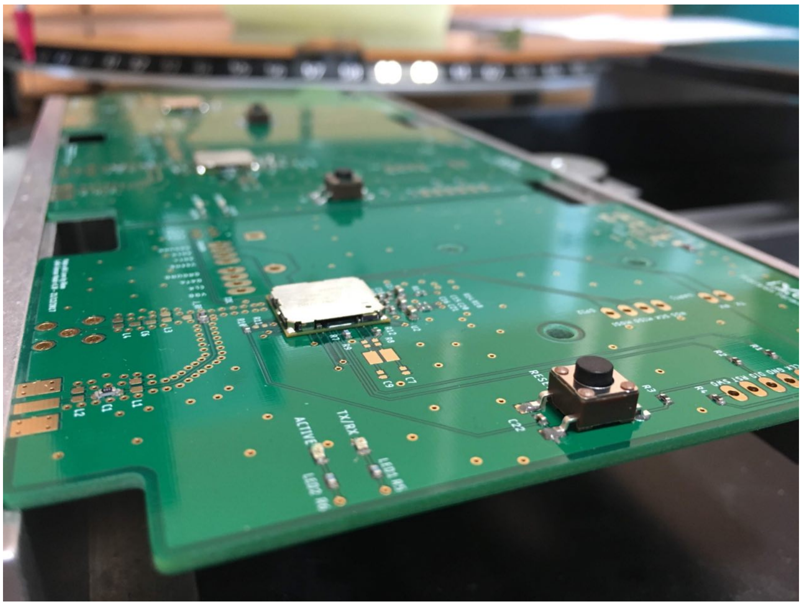

Figure 7.6.7: Component placing

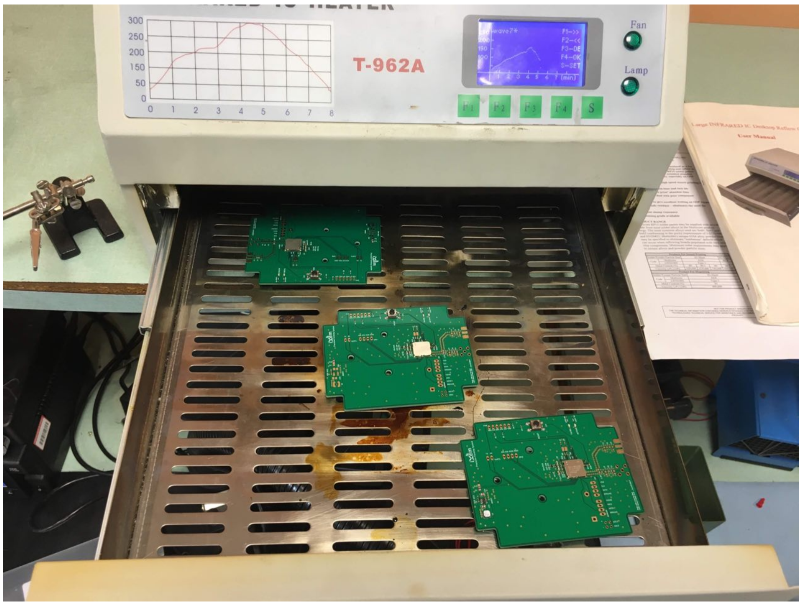

Figure 7.6.8: Soldering phase inside the oven

Figure 7.6.9: Open-node device

Figure 7.6.10: Open-node installed in a vineyard

8 Software Development

8.1 Tool-chain

The tool-chain used to develop the Open Node firmware is composed by the GCC (GNU Compiler Collection) and the GDB (GNU Debugger) tools. Those are classic and standard open source software used to compile and debug normal C application. In order to let them work with the chosen micro controller, various external libraries must be used to instruct the compiler and the linker that the underline architecture (target) is the given micro controller with all its own specifications. Finally, a programmer (in this case the ST-Link board) is needed in order to actually flash the firmware inside the micro controller, thanks to this SWD (Serial Wire Debug) debugger, it is possible to set breakpoints and to analyze the content of registers through the steps of microcontroller.

Even if the firmware can be developed by using only this tool, it is often more convenient to use an higher level application that helps the developer in a visual way. For example, display in a proper GUI the values of all the registers of the micro controller, or enable the debug step by step in order to test the written software. In order to achieve this the Eclipse IDE has been chosen.

Eclipse is an open source integrated development environment commonly used to write java application. Many plugins can be used to turn this software into a specialized IDE for a different programming language, such as C/C++, Python, PHP.

8.2 Code Architecture

One of the main issues to deal with is that the Open Node can be configured in different way from the hardware point of view (i.e. every device can be equipped with different physical sensors), so many different devices of the MCU can be enabled or disabled. For initial tests we use the full enabled configuration, but this causes the increase of power consumption. This is not a thing that can be accepted in a design which requires the lowest power consumption achievable. This is not only a problem for the development of the board, but also it needs to be handled by the firmware that must be aware of the current configuration. For the initialization code (boiler code), a tool called CubeMX (from ST)[27] has been used in conjunction with the manual for the microcontroller.

In order to separate the components, different sub-modules has been developed. Each one is loaded at compile time based on the value of a constant defined just before to build and flash the firmware. Using this technique, it is possible to extend the project to work with newly come physical sensor type, in fact it will only needed to add the new module that will be in charge to handle the new sensor type. This module will be then loaded and used by the main code that will only use it as it was a normal library.

Every module has to handle a different sensor type, so the hardware specification such as the ADC to use or the serial communication protocol to setup with the correct configuration will be hard-coded into each module. After the first test, once that the modules required during the thesis has been successfully setup and tested, a further step has been taken. The modules system has been updated in order to allow the device to handle more than one physical sensor types by defining a new module that will include the primitive ones. Of course, at this point the limit of the Open Node is defined only by the hardware, for example the limit of PIN available or the number of ADC that can be used.

As explained before, if we want to use an analog output device with the open node, which has an output in voltage, we need to set up the ADC. First of all, we select the configuration for the ADC controller, clock speed, clock source, conversion trigger (software or with compare or interrupt), conversion cycle (number of clock cycles before the input is considered stable), direction of scan, resolution, and so on. After we have to choose the right input pin for every channel desired and the correct functions to every port. For example, we have to choose port A and GPIO number 3 for the ADC3 input, we can also choose (for other kind of configuration) the presence of Pull-up or Pull-down resistor and a digital filter introduction or less. In other cases, we have sensors which directly communicate the dimension measured, like the SHT21, coming from Sensirion[28]. Using this kind of sensor let us to design only the communication part, assuming the correct the readings coming from the sensor. The SHT21 uses an I2C bus, so the device has to be configured with those characteristics. As on the ADC controller, we first have to configure the SHT21 handler, with clock speed, clock polarity, address of the device and surely the configuration of the port and pin as an alternate function GPIO pins.

Going more deeply in the scheme of the behavior of the chip, we can talk about the various operation made during the startup and during normal operation. At the startup, we set every useful variable at the default value, checking if the flash memory of microcontroller contains different values to use(for example personalized sleep time); then according to the HAL (Hardware Abstraction Layer), made by ST, we follow the recommendations regarding the different peripherals, initializing only the used or the preferred ones. In order to better understand what HAL is, there's some information in the ANNEX but it is not the scope of this thesis show how does it works. After the initialization we have our microcontroller ready and the radio chip already configured to work in the desired bands and geographical place. In the Commissioning.h file, are contained the information for the accounting of the sensor to the platform. As presented in the LoRaWAN specification, we follow the structure of OTAA (Over The Air Activation) so our device needs to connect to a LoRaWAN network server trough a gateway, in order to collect data and encryption key required to transmit data to the application. The OTAA is made only (mainly, otherwise requested) during the startup, after a power up or after a reset, the device tries 3 times in a row to reach the server. If something fails, it will be silenced for a time specified in ACCOUNTING_DUTY_CYCLE, and after tries back to connect, till the end of battery. Otherwise if the server replies to the device, it gives 2 different info to allow device to enter into the net. After this operation, the device goes to sleep, turning off every unnecessary peripheral, ant setting an alarm on the internal RTC, after every wake-up, most of the peripherals turned off need one more initialization before the usage of them. Then, during the awakening, device talks to the sensors, collecting information, and send those info troughs the LoRa communication directly to a various gateway in an asynchronous way, without an ack, and the come back to sleep. Time between two different readings or awakening is defined in SLEEP DUTY CYCLE. But using the sleep time across two readings is not enough to reach the lowest level of power consumption, because some sensors drawn a lot of energy, think for example to the anemometer, two times in a full rotation, calls an int errupt, so the device needs to wake up and serve the interrupt, using a big amount of energy only to collect a single bit information. But we are found a solution, instead using an interrupt which increase the value of a variable, ones per time, which imply the awakening of the device, we can use a TIMER. Another problem is that how use a timer, our idea was to put a 1 in the timer data line and give the output of anemometer, after a filter, to the clock line of a timer. So, after every rotation, the timer increases of 2 values; but the problem still remains because a timer can be used only during the run mode. Final solution of the problem is using the low power timer (LP_TIM) available in the STM32 architecture, which is clocked also with the 32kHz clock of Real TIme Clock (RTC), and that can be increased without the wake up of microcontroller .Thanks to this behavior we have reduced the power consumption of the anemometer close to zero because the only current drawn is the one needed by the LP_TIM. Regarding the transmission stage it's worth to make a note about the payload format of the measures sent. In order to reduce the size of data transmitted, a special payload format has been adopted to serialize the information in an efficient way. Cayenne Low Power Payload (Cayenne LPP)[29] allows the device to send multiple sensors measure reducing the payload size. Each sensor measure is identified by a tuple composed by the following information:

- Data Channel Number (1 byte)

- Data Type (1 byte)
- Data Value (1-9 bytes)

Every sensor measure has it's own Data channel number that is used to identify it among different sensors type attached to the open-node. The available Data channel type are listed in table 8.2.1. Each type has different resolution and unit of measure, for this reason the data size varies from one to another. After these information, the data value is inserted. This tuple is repeated for each sensor type attached.

Type	HEX	Data Size	Dara resolution per bit
Digital Input	0	1	1
Digital Output	1	1	1
Analog Input	2	2	0.01 Signed
Analog Output	3	2	0.01 Signed
Illuminance Sensor	65	2	1 Lux Unsigned MSB
Presence Sensor	66	1	1
Temperature Sensor	67	2	0.1 °C Signed MSB
Humidity Sensor	68	1	0.5 % Unsigned
Accelerometer	71	6	0.001 G Signed MSB per axis
Barometer	73	2	0.1 hPa Unsigned MSB
Gyrometer	86	6	0.01 °/s Signed MSB per axis
GPS Location	88	9	Latitude: 0.0001 ° Signed MSB Longitude : 0.0001 ° Signed MSB Altitude : 0.01 meter Signed MSB

Table 8.2.1: Cayenne LPP data types

This representation allow the server to easily deserialize the payload, but at the same time reduce at the minimum the overhead introduced into the message sent.

The final payload structure is showed in table 8.2.2.

1 Byte	1 Byte	N Byte	1 Byte	1 Byte	M Byte	...
Data1 Ch.	Data1 Type	Data1	Data2 Ch.	Data2 Type	Data2	...

Table 8.2.2: Uplink Payload structure. M and N depends on the size from the Data Type

Common LoRaWAN Network Sensor implementations already include the module to decode the Cayenne LPP standard. This help the quickly prototyping of a simple web service to receive and operate over the measurements, since the data is already decoded and ready to be used.

An example of Cayenne LPP is reported below:

Supposing to have a device with two temperature sensor that transmit a message containing the Payload (HEX) : 03 67 01 10 05 67 00 FF

The decoding of information is reported in table

Data Channel	**Type**	**Value**
03 - 3	67 - Temperature	0110 - 272 - 27.2°C
05 - 3	67 - Temperature	00FF - 255 - 25.5°C

Table 8.2.3: Cayenne LPP information decoding example

Part IV

Open-Node Validation

9 Meaningful results

To date, the iXemWine is an official project of Politecnico di Torino. The first part of experimentation started in April 2018, it was useful to validate the correct functioning of the Open Node and to carry out concrete tests on the possibility of creating an extensive data collection network. In March 2019, instead, the platform was officially presented within an event at the Polytechnic. From that moment, the second phase began and it consists of the dissemination of the network and the collection of data at national level. Now the iXemWine network provides LoRaWAN coverage in five italian regions: Piedmont, Campania, Friuli Venezia Giulia, Tuscany and Sardinia. Furthemore, the iXem Labs is planning to extend this network also in other regions.

More than 40 LoRaWAN gateways have been deployed to create the iXemWine network. Thanks to it, more than one hundred working Open- node devices sends data to the application used by 476 users. A map with the position of all vineyards is shown in the figure 9.0.1.

In the following, some of the meaningful results obtained are presented. From the power consumption points of view, we can take a look to the first Open-node installed in Tuscany at the Poderi Boscarelli winery. It's a single face leaf wetness activated on 10 April 2018 that have send more than 66,000 measurements without interruption and still have the 76% remaining battery power. In the figure 9.0.2, the battery discharge graph from the beginning is presented.

From this information, it is possible to see how the work carried out during the design phase has led to the required results.

Other meaningful results are obtained from the communication point of view. The best communication distance has been achieved from the Mosconi vineyards of Conterno Fantino winery in Monforte d'Alba and the gateway installed in Gattinara. The total distance obtained is 117 kilometers in line of sight conditions. This result is showed in figure 9.0.3.

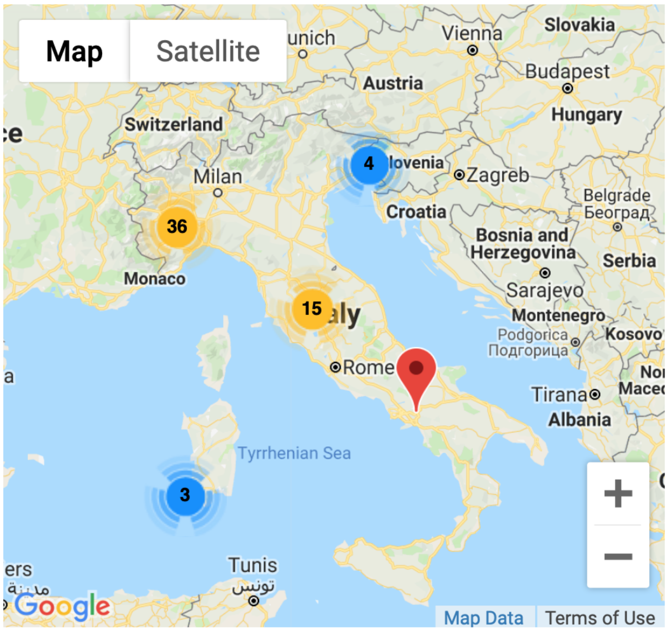

Figure 9.0.1: Vineyards distribution map

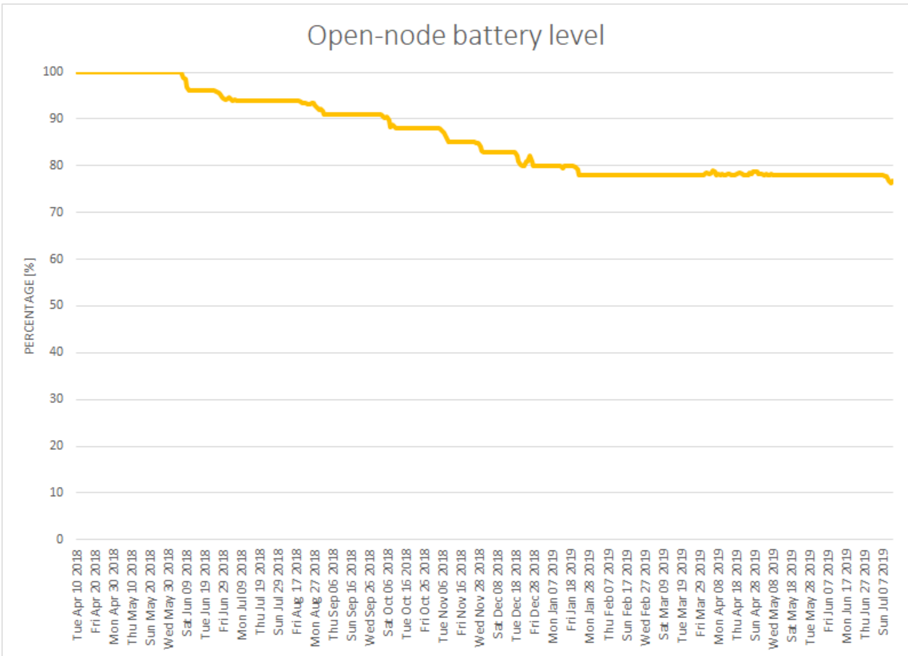

Figure 9.0.2: 1st Open-node battery discharge graph

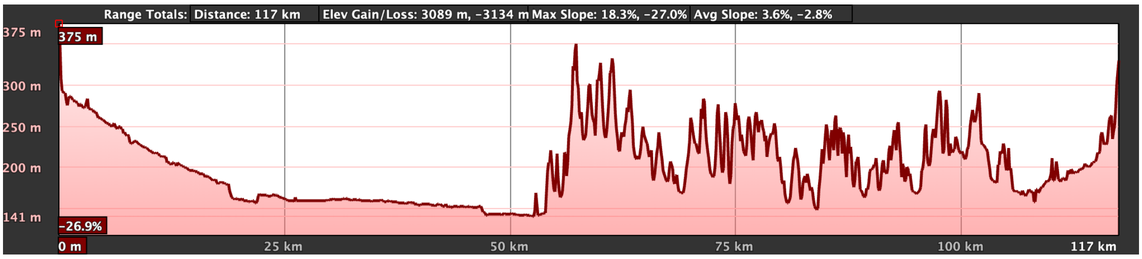

Figure 9.0.3: Elevation profile between Open-node in Mosconi vineyard and gateway of Gattinara

The last result that I want to present is always related to communication performance but, in this case, in a No-line of Sight conditions. The outcome have been achieved in Montepulciano, Tuscany, where the Open-node was able to reach a maximum distance of 11 kilometers without line-of-sight (figure 9.0.4).

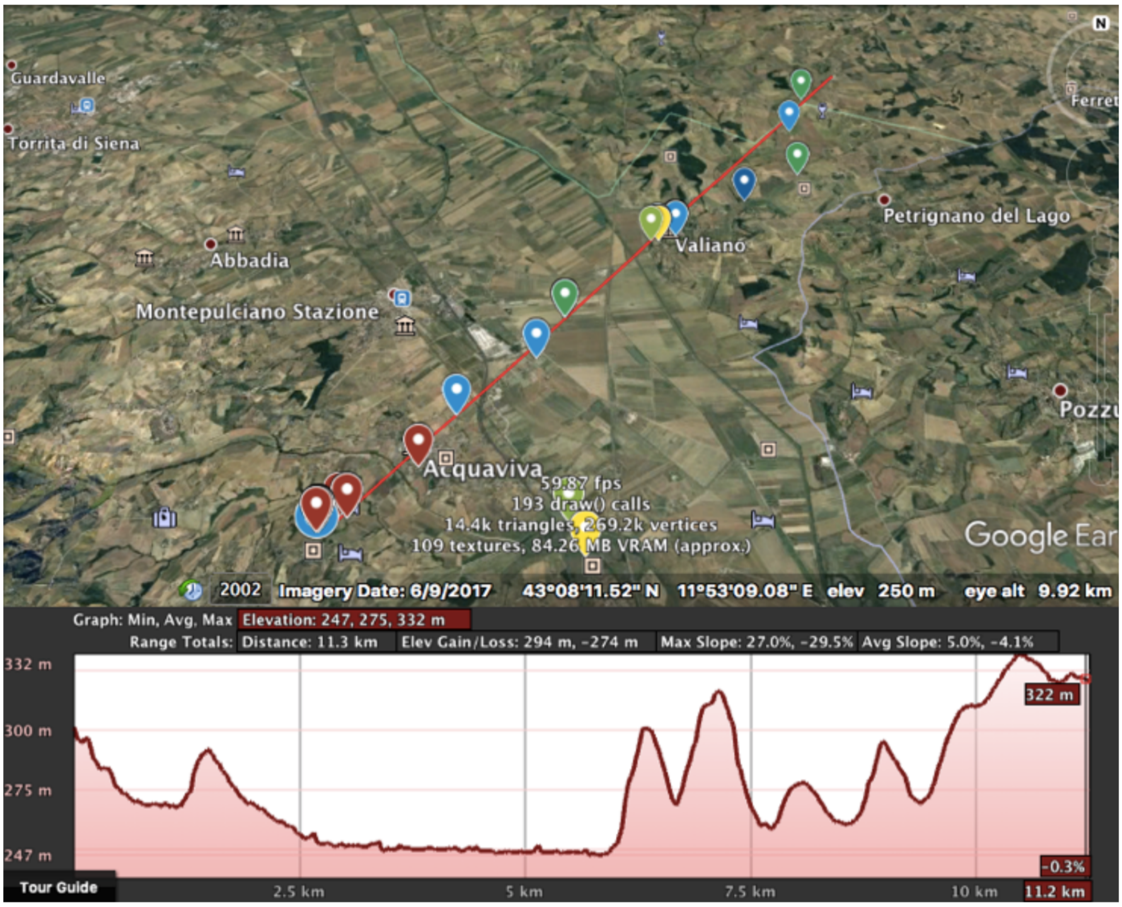

Figure 9.0.4: Altimetric profile (below) and measurement results between Cervognano and Centoia. Values vary between -70 dBm (red) and -120 dBm (blue)

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