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“Wireless temperature sensing in hostile environments using a microcontroller powered by optical fiber”

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Finalizar este trabajo significa terminar cuatro largos, duros y maravillosos años de mi vida. La línea de separación entre el esfuerzo y el éxito es tan pequeña que es casi imperceptible, y tirando de tópico puedo asegurar que todo lo que en esta vida supone un esfuerzo merece la pena.

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ABSTRACTO

Uno de los mayores riegos del mundo industrial es el fallo de las maquinarias y aparatos que los forman. Un error, provocado por la causa que sea, puede tener consecuencias fatales, no solo para la empresa sino también para todo su entorno. Estas máquinas trabajan con altas cantidades de energía, por lo que su control y monitoreo disminuye los riesgos y asegura una mayor seguridad a la hora de trabajar con ellos.

Un ejemplo de este tipo de máquinas son los transformadores. Estos dispositivos trabajan con circuitos eléctricos que intercambian altas cantidades de potencia para el funcionamiento y distribución eléctrica. Existen distintos parámetros a medir para poder monitorear el estado en que se encuentran estas máquinas, pero uno de los principales es la temperatura, y en ese se va a basar este proyecto.

Controlar la temperatura de un transformador supone controlar el interior del mismo, y con ello asegurarse de que funciona correctamente, y que sigue en el periodo de su vida útil, ya que el envejecimiento y desgaste de esta puede llegar a generar graves consecuencias.

La temperatura se va a medir utilizando un sensor de instrumentación. Para su diseño, la principal característica a tener en cuenta es la necesidad de que se adapte al entorno hostil que rodea a los transformadores. Es por ello que se va a utilizar un sensor de fibra óptica, inmune a las interferencias electromagnéticas y de radiofrecuencia, y garantizando un bajo coste.

La información del sensor se va a obtener con un microprocesador, conectado en el punto de salida de señal del sensor. Este dispositivo va a obtener la data correspondiente y la va a transmitir al módulo de comunicación, encargado de emitir los resultados a la unidad de control.

Como sistema de comunicación, se va a utilizar un protocolo inalámbrico. El protocolo ZigBee asegura una robustez y rápido start-up, así como un diseño simple y sencillo.

Finalmente, la interfaz de ordenador se va a diseñar con el programa LabView. Va a tener la funcionalidad de punto de control, con la capacidad de activar el funcionamiento de la red sensorial, y su casi inmediato monitoreo. Eso es, que la interfaz estará diseñada para obtener la data emitida por el sensor, y analizarla, dándole al usuario la información correspondiente, casi en tiempo inmediato. Por lo que es posible conocer, casi al momento, la temperatura a la que se encuentra el sensor, por ende la temperatura en el transformador.

En caso de requerir un sistema totalmente inmune a las interferencias electromagnéticas, la alimentación del sensor se podría hacer a través de la tecnología PoF (Power over Fiber). Utilizando un sistema ya diseñado e implementado de la universidad, se van a adaptar sus parámetros a los

requerimientos del sistema para observar sus resultados, tanto teórica como experimentalmente.

Este proyecto consiste en el diseño e implementación de todos los distintos componentes del sensor de temperatura, es decir, la fibra óptica y sus circuitos de adaptación, la programación del microprocesador, el establecimiento de la comunicación inalámbrica, y el diseño de la interfaz.

Una vez implementado todo el sistema, se van a realizar distintas pruebas, donde se va a someter al sensor a bruscas variaciones de temperaturas para estudiar su respuesta. Y una vez comprobado que todo el sistema funciona correctamente, se va a sustituir la fuente de tensión, por la tecnología PoF, observando los resultados y su posible futura inclusión en el desarrollo de sensores.

ABSTRACT

One of the greatest risks of the industrial area is the failure of the machines and devices composing in. Any mistake may have fatal consequences, not only for the industry but also for its environment. These machines work with high quantities of energy, so its control and monitoring decreases the risks and guarantees a greater security when working with them

The transformers are an example of these machines. These devices work with electrical circuits exchanging great amounts of energy for the electrical distribution. There are different parameters that will enable the monitoring of the machine´s state, but one of the main ones is the temperature, and it is what this project will focus on.

In order to control the temperature of the transformer, the sensor must be placed inside of it. This means one of the main characteristics of the designed sensor has to be its immunity to electromagnetic and radiofrequency interferences, this is why it the selected sensor uses optical fiber.

The data acquisition is going to be done with a microprocessor, which will be connected to the sensor and programed to obtain the results and transmit them to communication module, which is set to emit them to the control unit.

The communication is going to use a wireless protocol. The ZigBee protocol is going to provide roughness and fast commissioning, as well as a simple and nice design.

The control unit is going to be designed with the LabView program. Its programming include the acquisition of the data received from the sensor and its analysis. This means it will take the results and give the user its equivalent temperature value, almost immediately to the response of the sensor. This way it is possible to know the temperature the sensor is at, hence the temperature of the transformer.

In case of requiring a system totally immune to interferences, the system will have to be powered with a PoF technology. A PoF system already designed and implemented is going to be adapted to the system, and tested to read its response.

The project consists on the design and implementation of the sensor temperature, and all its components, this is the optical fiber and its adaptation circuits, the microprocessor´s programming, the communication and the interface design. Once the whole system is implemented, different tests are going to be done where the sensor is going to be submitted to abrupt temperature variations and its response studied. Once checked the system is working correctly the power source will be replaced with the PoF, analyzing its results and future inclusion on the sensors development.

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Chapter 1
INTRODUCTION

1.1 INTRODUCTION

The following project is framed around the risk that uncontrolled temperature values entails in the power transformers used nowadays. It gives a viable solution to the monitoring and control of the machines, assuring its longevity and guarantying the precaution methods.

The power transformers are devices used in the electric distribution systems, using high values of power, around 500 kVA, which results in high risks for the environment with great repercussions. The temperature is one of the main characteristics of these machines, and its control is key to a successful operation.

This project proposes a novel technique to measure the temperature inside of the transformer, using an optical sensor and wireless communication to make sure the devices are working under correct circumstances. The control will be done remotely with a programmed interface, using the computer program LabView, which will receive the data and process it. It guarantees an easy understanding for the user and an error detector to assure the functioning.

The design of the sensor was determined taking into account the limitations the selected environment presents. It was key to choose one that included low cost, low consumption and a reduced size for an easy installation as its most basic characteristics. From the different technologies commercially available nowadays, the use of an optical sensor was determined as the most suitable option for industrial environments involving transformers, benefiting from its immunity to electromagnetic interferences characteristics.

When determining the communication protocol the decision of using a wireless system allows a non-physical propagation mode through relatively long distances, which uses electromagnetic waves and a determined frequency for the transmission between devices. The main advantages were the low costs and easy and clean installation based on the reduced size of the devices. It permits a large coverage, allowing reaching more delicate spaces because of the non-use of cables. The selected protocol was ZigBee; taking into account the roughness it provides, essential for the environment the sensors will be located at. It allows a long distance scope and a fast recovery, in case of failure.

After the development and testing of the system via traditional electric power source means, next step was considering feeding the system via power over fiber (PoF) techniques. In this last stage of the project and in collaboration with a PhD student from the Electronics Technology Dpt. (DTE) at UC3M, Juan Dayron Lopez Cardona (julopez@ing.uc3m.es), the developed system was tested to check its response by alternatively powering it via PoF. Measuring the maximum distance at which the Arduino One plate can be powered. Two different methods were tried out, and the results analyzed to see if it was a suitable option for remotely powering the components, instead of the electrical source.

The project will deep to a greater extent in the justification of the selected resources, including comparisons with the different options studied and the reasons for the final selection. It will also include the final design of the sensor, and the results experimentally obtained at the lab facilities of the full-developed system, including every aspect discussed.

1.2 SOCIAL ECONOMICAL IMPACT

The development of power transformer plants has great implications in the territories where they are run. The transformers work transferring electrical energy from one circuit to another, weighting tons and connecting power networks between one to another. The operation of the devices can end up having different effects, like the contamination caused by the carbon dioxide emitted from burning the chemical products that maintain the device active. If these products are released into the environment they can also result to be harmful. The animal´s habitat are affected by the contamination, and by the second effect of the transformers, the electromagnetic fields emitted from them, which can also generate health problems.

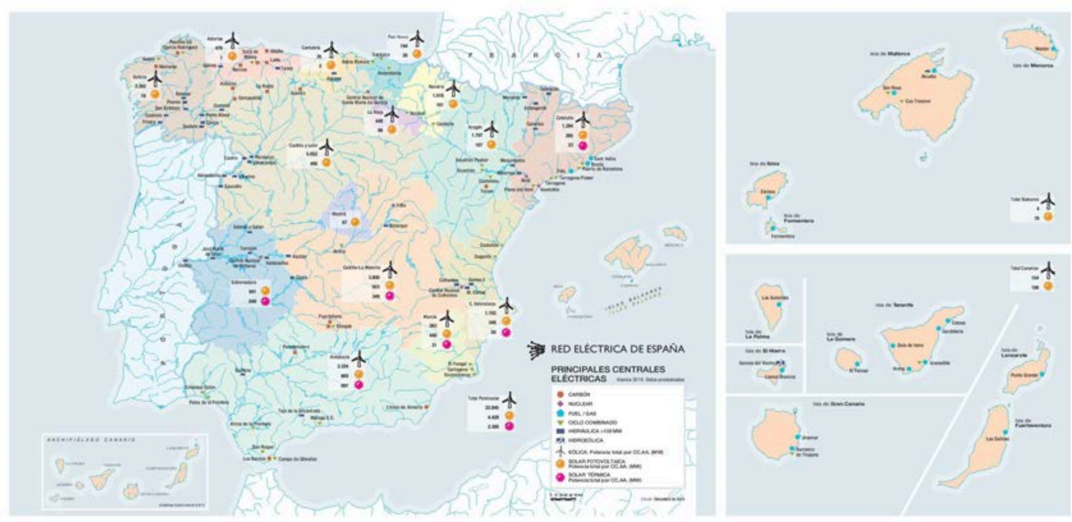

Figure 1.1. Map of power plants in Spain [1]

An example of the implications a failure in the transformers system has, is the terrific accident that took place in a hotel in Tarifa, Cadiz. An electrical transformer exploded causing eight people to get hurt, with burns that go from 50 to 90 % of the body [2]. Hence the importance of a successful monitoring process, that warns before catastrophes such as this one take place.

As previously mentioned, one of the most dangerous effects of the transformer is considered to be the electromagnetic fields, present everywhere and invisible to human eye. They are produced due to an accumulation of electricity. And the consequences these electromagnetic interferences may have for the human health have resulted in precautions the workers whom are in contact with these fields must take.

Based on these two points, it is required somehow to control and monitor the performance of the transformer, to assure it is properly working and to avoid any failure and its terrific consequences. But the risks the closeness to these machines has upon the workers make it also indispensable to do the evaluation of the data obtained remotely.

Nowadays the wireless net has considerably grown based on the conditions of freedom for use, mobility and flexibility, being a resourceful communication method for the industry, telco operators, and digital homes.

The variety of sensors of low cost, low consumption and reduced size along with the wireless transmission capabilities allow nets able to process large quantities of data. The selected sensors decrease the cost of the project and assure a low consumption that ends up in longer useful periods and lower maintenance. The wireless communication maintains the low cost budget, not needing any cable or wire, or its required adaption to the environment in which it will be installed. These characteristics make it one of the most used communication resources nowadays, and the developed protocols include low consumption and a large data transfer.

The great dimensions and the hard access to determined places inside the transformer increase the difficulty of the maintenance. The wireless net allows a non-intrusive method capable of monitoring a high variety of parameters. The no-need for cables and small size of the sensors reduce the visual impact, being able to integrate in the environment and transfer the acquired data.

The main focus is the development of an instrumental method for the monitoring of power transformers. These aims to increase the safety of the working area and reduced the exposition of the workers, using an easy to understand interface that allows to control those parameters remotely.

1.3 OBJECTIVES AND CONTENTS

The objective of this project is to remotely interrogate and measure the temperature inside a transformer using an intelligent sensing method that includes an optical sensor and a microcontroller. The latter will be powered by optical fiber means, thus implementing Power-over-Fiber (PoF) technology.

The development of the system can be divided in both theoretical and experimental tasks.

First, the theoretical part of the project will focus on the justification of the selection of the used resources. All possible options for the required components will be studied and analyzed, comparing the possibilities and explaining what makes it the most suitable for this project. This includes:

- The selection of the optical fiber sensor, what makes it the best option in this specific project, taking into account its characteristics compared to the other sensor's features.
- The design of the electrical circuits to operate the sensing scheme. When employing optoelectronic devices, such as optical sources and optical receivers, it is necessary to design the adaptation circuits that go along with. The development of this electronic stage will include the reasoning used for the selected parameters that compose it, and the theoretical results obtained from these designs.
- The selection of ZigBee as the communication protocol, including its most remarkable characteristics for the project and the definition of the device used for its inclusion, the XBee modules using the Arduino plates.

The experimental part of the project focuses on the development of the system at the lab facilities at the DTE. After the analysis of the components, and the selection of their parameters, the operation of the system will be tested. This includes:

- Developing the circuits based on the selected design. Assuring it is properly working and the results obtained experimentally are similar to the theoretical values. The theoretical values are obtained assuming ideal circumstances, which means it is possible the experimental results may not be exactly the same.
- The data acquisition. This process will be done using the microprocessor in the Arduino One plate, which will be programmed to obtain the data from the output signal of the circuit and transforming it. The analogical value will be converted into a digital one for its transmission to the communication module
- Programming both XBee module antennas, connecting one to the other and setting a communication link between them.

- Obtaining a calibration curve of the temperature values. This curve will compare the voltage value obtained from the circuit; to the temperature the sensor (which will be placed on a hot plate) is set to be. In this way a linear function relating both values will be obtained, and will be used in the final interface for the temperature analysis.
- Development of the computer interface using the LabView program. The program will receive the information from the sensor and will use the calibrated function to obtain the temperature value that will then appear on the user screen. The program will also include alarms, warning the workers when the temperature values are outside of the correct, previously set, thresholds.

The final results obtained from the project show the full operation of instrumental systems, including every aspect from the design to the implementation.

After developing and testing the system, the electric power source used will be replaced by PoF technique. In order to obtain the maximum and minimum electrical consumption values of the system, an analysis of the consumption in the emitter Arduino plate will be done. The feasibility of powering the Arduino module though PoF will be theoretically studied analyzing the power budget.

A testing bench will be design over the PoF schematic in which the longest distance capable of powering the Arduino plate will be measured.

1.4 PROJECT SCHEDULE

The following points will describe the activities performed for the development of the project, as well as the estimated time dedicated to its implementation:

I. **Documentation and state-of-the-art**
   - *a.* Mechanical, electrical, magnetically or optical sensors to measure the temperature.
   - *b.* Advantages and disadvantages of the proposed sensors.
   - *c.* Identification of the measuring techniques that avoid the use of electrical components for the temperature measure in hostile environments.
   - *d.* Advantages and disadvantages of the measuring techniques proposed.

(2-3 weeks)

II. **Complete instrumentation system design** that allows measuring, amplifying and filtering the electrical signal from the temperature sensor. This will always be done while the used sensor does not have a signal conditioning circuit involved. The instrumentation system will be simulated using Multisim tool with the aim of justifying the utilized components and adept their values to obtain an adequate output signal.

(1 week)

III. **Analysis of the characteristic parameters** of a temperature sensor, such as sensitivity, calibration curve, linearity, among others.

(1 week)

IV. **Development of the instrumentation system** using a photo-board plate.

(2 weeks)

V. **Design of the Arduino program** that allows acquiring the analogical signal. The digital signal will be transmitted through a ZigBee module to another Arduino Uno that will be in charge of transmitting from a USB to the computer. The modules programming will be done through LabView.

(2-3 months)

VI. **Consumption analysis of the Arduino emitter module** with the aim of determining the maximum and minimum consumption of the system. Theoretical study of the viability of powering the Arduino plate through Power over Fiber. In order to do so a power budget analysis will be done.

(2-3 months)

VII. **Design of a test bench over the Power Over Fiber schematic** in which the maximum distance at which the Arduino module can be powered. Juan Dayron Lopez Cardona, a PhD student from the university, will collaborate within this task.

(1 week)

VIII. **Discussion** over the application of the sensing system in the remote data acquisition and measurement of physical magnitudes in hostile environments.

(1 week)

IX. **Identification of possible future action lines** that will improve the work done.

(2 months)

X. **Elaboration of the project report**. Including diagrams of temporal planning and the project estimated budget.

(2 months)

XI. **Elaboration of a presentation for the project**

(1 week)

The following figure includes a Gannt diagram of the project, this is a graphical tool whose objectives is expose the predicted dedication time for different tasks through a total fixed time.

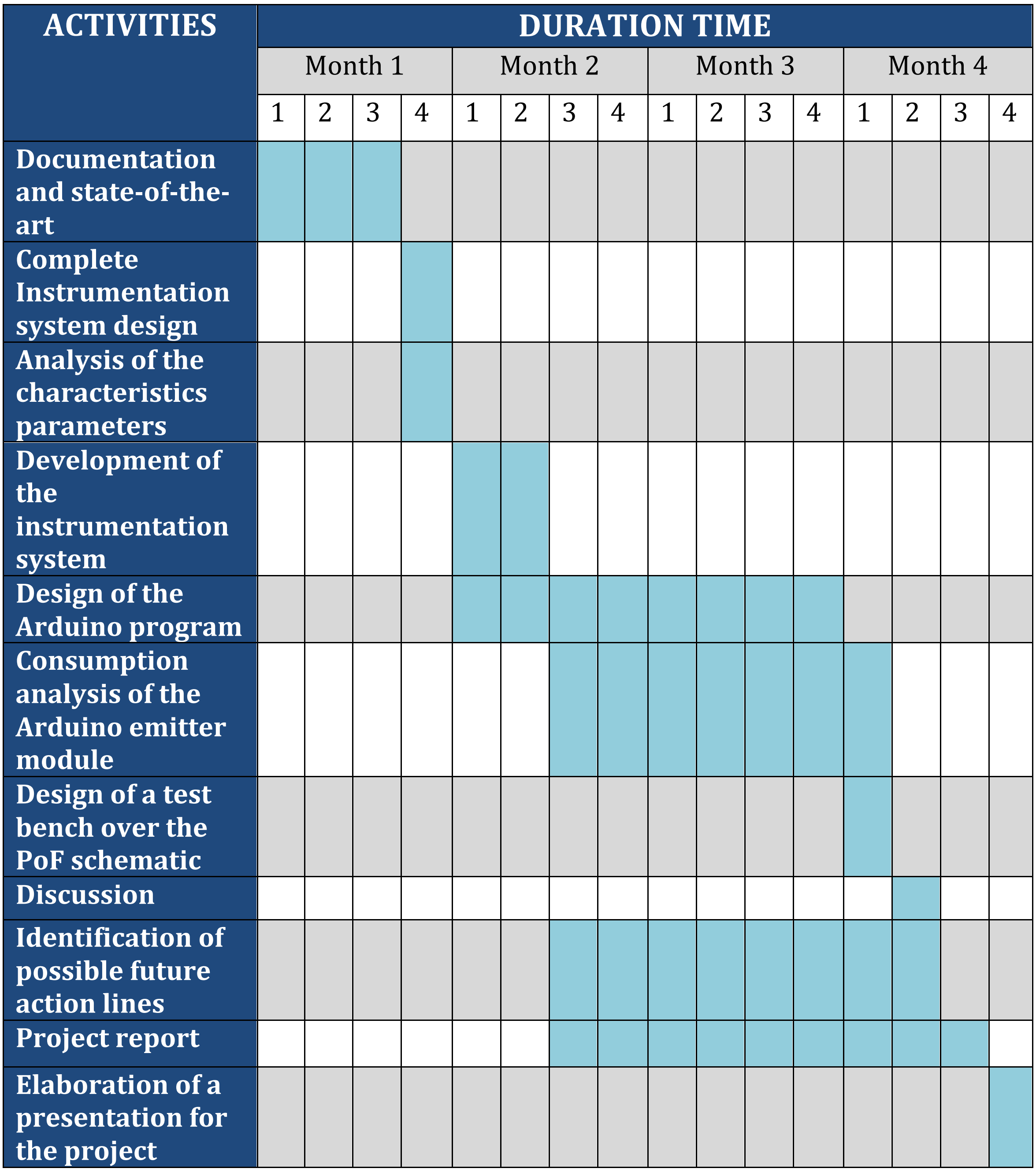

Figure 1.2. Gantt Diagram

Chapter 2

TEMPERATURE SENSORS

The temperature is one of the main parameters in many industrial operations. This physical property is able to provide features to the process that allow us to make sure it is a safe environment to work, or to monitor the performance of devices and equipment.

An example of the use of the temperature monitoring could be the plastic industry. In this case there are different types of processes with different goals, but the same idea, the alteration of the material. In order to do so several different temperature ranges have to be monitored and analyzed to reassure the high quality level of the final product. Normally uses devices with infrared technology for the measurement that can sustain the extremely high temperatures. Another example can be the automotive industry, which shows the importance of the temperature through an industrial process where the temperature of the factory has to be indicated in order for the machines to work correctly as the products go through the different manufacturing stages there are infrared thermometers that monitor and optimize them. There is also the medical area, which uses non-contact temperature measurement so products can be monitored and provide a fast diagnosis.

The three mentioned industries are three examples of the effect of the temperature and its importance in processes that require a preventive maintenance. The temperature sensors can detect the heat spots, which in industrial factories turn out to be the weak points or defects. The analysis of this parameter can help avoid catastrophes due to a machinery failure, also assure the longevity of the devices functioning life, and increase the safety of the workers environment.

The preventive maintenance is one of the most important characteristics of any industry, especially in those working machinery with great amounts of power, because it assures the efficiency of the process and decreases the risks of the working environment. An example of these powerful machines is the power transformers, used for energy distribution. They work with high electrical voltages, and use electromagnetic induction to transfer energy between several circuits. The failure of these devices can cause a great cost to the owner, and result being harmful for the environment. The risk of a wrong performance of the transformers increases with the age, because it causes an internal degradation. Monitoring the temperature allows to estimate the loss of life caused by this overheating process. The preventive maintenance of a transformer allows obtaining an early diagnosis and anticipation of possible breakdowns.

In order to measure the temperature in an industrial process there are different commercially available sensors that are ruled by different laws of physics. Depending on the sensor features the limitations and needs of the working environment, the selection and analysis of the sensor becomes an important step in any project development that involves an instrumentation system.

For an easier resolution of the selection, the sensors are going to be categorized in three main different types: mechanical, electrical and optical sensors, that involves mechanical, electrical/electronic or optical parameters and quantities to be interrogated and analyzed, respectively.
The mechanical devices modify their behavior under the action of a mechanical magnitude (force, displacement, inertial, flow…) that can directly or indirectly transmit a signal to indicate change. The electrical sensors can be of different types, such as semiconductor or metallic-based. The first case usually employs the change in the electrical current with regards to the measurement of interest. The metallic (resistive) sensor applies the same method, i.e. the resistance varies as the temperature changes. Along with the resistive, there are also the inductive and capacitive sensors, which have the same performance methodology, but with different magnitudes. In the case of optical sensors, the latter use any of the physical properties of light to sense the magnitude of interest.

After this basic introduction of the three main sensor types in our industry, a more complex and deep analysis of each of the sensors is going to be made, to assure the most fitting and optimized selection for the temperature analysis in the transformer.

2.1 MECHANICAL SENSORS

They measure physical magnitudes such as displacement, velocity, acceleration, mechanical force, rotation, bending and pressure, among others. Devices such as thermometers are a commonly used example of this type of sensor.

- Thermometer: is a device that allows the measurement of the temperature and its changes. The quantification of the temperature is a process based on different international scales, like Celsius and Kelvin.
  These sensors are widely used to control and monitor processes. The most typical thermometer is the mercury-in-glass type, based on the mechanical dilatation of a mercury column inside a bulb that is attached to a glass tube. The volume change of the mercury varies with temperature, and drives it up the tube, giving a numerical result.
  The features of this sensor include the good conduction of heat, the low vapor exertion and the uniform expansion, covering a typical range from -37ºC to 356ºC. One of the main disadvantages of this sensor is that it is not the most accurate method, because the temperature variation has to be large in order for the thermometer to show it [3].

The factors to consider when selecting a thermometer are:

- Accuracy
- Sensitivity: distance between divisions on the scale
- Range: of temperatures it can measure
- Speed of response: measure rapidly varying temperatures
- Easy to read, with non-complicated calibrations
- The sensitive component of the thermometer should be small so that it does not absorb much heat from the object

There are also infrared thermometers, which are not categorized as mechanical sensors but as thermal radiation sensors. However it is interesting to understand this kind of sensors as well, because of its frequent use in industrial processes. These infrared thermometers are non-contact devices that measure the infrared energy, the thermal radiation emitted by an object. They provide fast and accurate values, being especially useful in the process with contamination risks, where the item being measured should not be touched. They allow acquiring the temperature of moving objects, and they are compact and easy to use [4]. This, however, is not an option when measuring the temperature inside of a transformer, because it is not able to measure gas or liquids, it cannot be used in hostile environments with any dust or humidity, and the accuracy may be affected by these factors.

2.2 ELECTRICAL SENSORS

Electrical sensors are the most used when measuring temperature in industrial processes, because of the wide variety of off-the-shelf sensors. These devices transform the temperature changes in electrical magnitude variations, processed by electronica components. They use electromagnetic magnitudes such as electric fields, voltage, electric current and magnetic fields. The main types are:

- Resistance temperature detectors (RTD): build with alloy metallic wires which resistance increases along with the temperature. These devices always have positive coefficients, and allow accurate measurements, because of the very linear output signal. However, it has a low thermal sensitivity (1Ω/ ºC), which means that a small temperature variation is almost negligible in the output result.
  There are different types of RTD, characterized by the material of the metals, which limit the temperature range that the resistance is able to bare.

Material	Temperature Range [ºC]	Variation Coefficient [%/ºC] at 25ºC
Platinum	-260 to +630	0.39
Nickel	-80 to +320	0.67
Copper	-200 to +260	0.38

Table 2.1. Values of temperature range and variation coefficient for Platinum, Nickel and Copper [5]

In this table 2.1 we can observe the temperature range of each of the main materials used for these devices, as well as the variation coefficient based on the temperature change, quantification the response of the detector to this alteration.
The most common RTD sensor is the Pt_{100}. It is made of platinum, which is the most stable and exact material. The 100 stands for the standard (nominal) resistance value (100 Ω) at 0ºC. The disadvantage of this exact sensor is the high cost of the platinum, resulting in an expensive option.

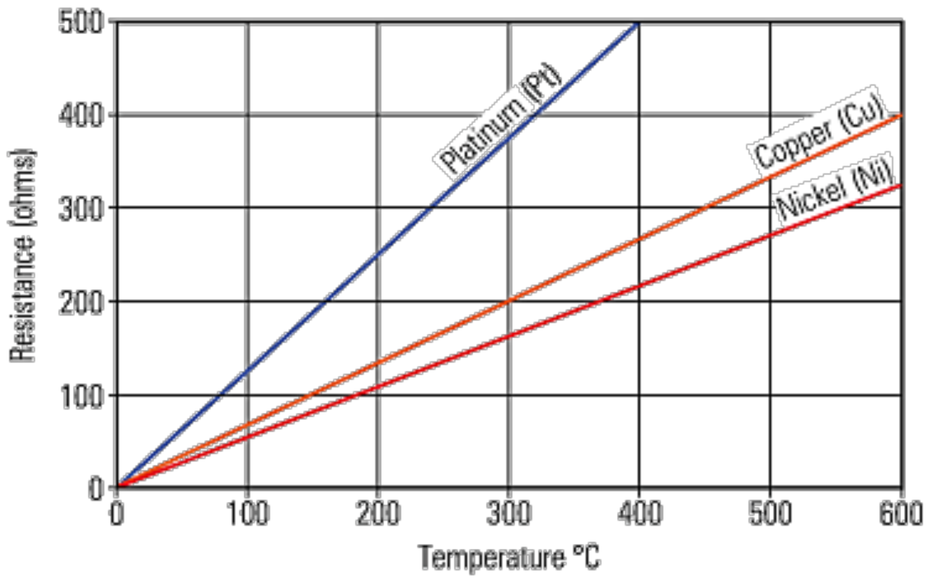

Figure 2.1. Resistance variation with the temperature [5]

The concept of this thermo-resistor is that current goes through the conducting material, obtaining and output voltage that increases with the temperature. Fig. 2.1 illustrates the variation of the resistance value when increasing the temperature affecting it. This power supply method can also cause the biggest failures, generating high risks of overheating the resistance producing errors in the final results.

- Thermistors: they share the same principle of operation as RTDS, i.e. the sensor varies the material resistance when temperature varies. The sensors are built with oxide metallic semiconductors which resistance decreases as temperature increases; hence they are referred to as Negative Temperature Coefficient (NTC). The materials are typically coated in glass, and the oxides normally used are nickel, manganese and cobalt. The glass coating makes them

fragile devices. They are composed with a time constant, which measures the time reaction to the temperature alteration, and a power rating, affected by the current going through.
The thermistors have a low linearity, however they can be linearized placing a resistor parallel to the NTC. Unlike the thermo-resistor, the thermistor has a high sensibility capable of decreasing 6% the resistance value for 1ºC raise. This high sensitivity allows a precise quantification of temperature, and a range of +140ºC to +450ºC. Their small size grants placing them in difficult spaces, which makes them ideal for some industrial processes.
The high sensitivity provides a fast response to any changes, but does not offer accuracy and stability when comparing to other electric sensors like the thermo-resistor. Also having the same overheating issue as the sensor previously mentioned, caused by the current going through the device, makes this option negligible for the temperature measurement inside the transformer [6].

- Thermocouple: the most used device in temperature measurement because of its wide measurement range, usually ranging from -200ºC to +1400ºC. They are based on the "Seebeck Effect", which consists on the generation of a thermoelectric voltage produced by the difference between the junctions of two conducting cables of different materials at a given temperature. The joint is associated as the reference joint, or "hot junction". To generate the voltage it needs a second junction at a different temperature, called the reference joint, or "cold junction". The output voltage of a thermocouple is a function of the temperature changes. It is important to highlight that the sensitivity has low numeric values, around μV/ ºC.

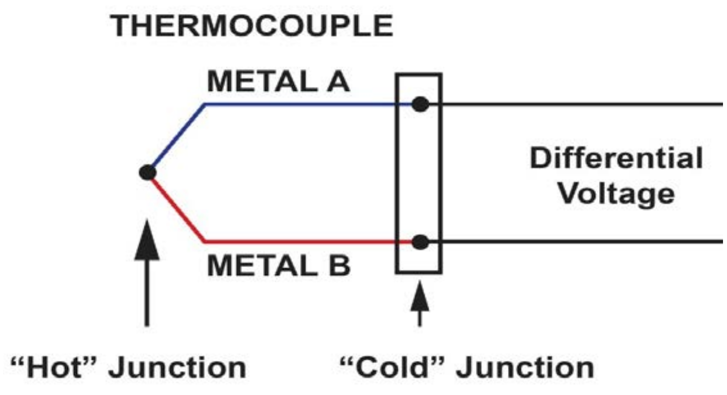

Figure 2.2. Thermocouple Schematics [7]

The fig. 2.2 is a schematic of the design of the thermocouple. The simplicity of the sensor facilitates the use, and allows a fast response due to the small size. The thresholds of the sensor are versatile, because the two metals used in the process set them. Due to the enormous possibilities resulting from the different material used, there are several international recognized standards, to ease the use in the diverse applications. The most common ones are the following, see table 2.2:

Code Type	Conductor (+/-)	Temperature Range [ºC]
J	Iron-Constantan	0 to +750
T	Copper-Constantan	-200 to +350
K	Nickel-Constantan	-200 to +1250

Table 2.2. Conductors type composition and temperature range [7]

They enable their use in oxidant environments. In the case of the J type, the iron oxidizes quickly and has a fragility potential, but with the advantage of a low cost. The biggest limitation of the T type is the low temperature range. The type K has the biggest output voltage signal, especially useful in humid environments because of its high resistance to corrosion.

2.3 OPTICAL SENSORS

The third type of sensors is optical sensors or fiber-optic sensors. They transform a physical magnitude into an optical parameter to measure it, like wavelength, light intensity, light phase, polarization. They usually employ an optical fiber to guide the light for their operation, although not always necessary.

One of the greatest features of these sensors is their immunity to electromagnetic (EMI) and radiofrequency (RFI) interferences, which makes them ideal for industrial processes working with great amount of power energy. Light is passive by nature and because they do not use electrical current they are suitable of operating in areas with high risk of explosion. Their easy design and simple installation allows placing them in difficult places.

Considering that the final purpose of the temperature sensor is to measure the temperature inside of a transformer, it is a clear that the final choice is the optical fiber. The mechanical and electrical sensors grant great features, with high sensitivities to the temperature changes and quick response, but because of the risk of working in an environment with high energy power, this means a very hostile electromagnetic interference environment, and risk of sparks the electrical sensors are completely discarded. Mechanical sensors are not also a valid option either due to the complexity of the contact with the machine. This leaves the optical sensor, being the most suitable option when working in industrial processes such as the transformer within power plants, with the main advantage of providing immunity to electromechanical interferences (EMI) that can alter the final results due to the passive nature of light [8].

2.3.1 Introduction

The most frequent use of the optical fiber cabling technology is in telecommunications and data transfer systems, although the sensing community has been always aware of the continuous fiber performance evolution. Nowadays the fiber-optic sensors benefit from the multiple advantages of optical fiber and optics. This type of sensors exhibit a set of very attractive characteristics, including immunity to electromagnetic and radiofrequency interference, increased sensitivity, passiveness, resistance to hostile environments, flexibility, geometric versatility, ruggedness, biological compatible, sensor multiplexing and distributed sensing over a single lead fiber. However it does have the disadvantage of high costs, compared to other technologies as well as the unfamiliarity to the end user.

Intensive research and development efforts have produced a large body of fiber-optic sensor technology [9], based on both multimode and single-mode fibers. Considering the multimode optical fibers, an optical sensor for monitoring the corrosion of aluminum alloys is reported [10] in with applications in modern military aircraft maintenance. On the other hand, single-mode fiber optical sensors have also been widely employed as reported in [11] in which self-referencing fiber-optic pressure sensor is developed on a white light Michelson interferometer obtaining dynamic ranges from 0 to 38.08 MPa with a resolution of 0.03 MPa.

The characteristics of the specific fiber-optic sensor come from the selected material. In this project will be using plastic fiber-optic, because it is more flexible than the slice material sensor, and also has a lower cost. Its frequent usage is a result of the small Young modulus of the coating and large core diameter, which makes it the rougher sensor, and barely affected by external media, a remarkable feature in these environments. It is easy to handle, and reduces significantly the maintenance and process costs. It has a large temperature range, covering the transformer´s, which is one of the main requirements for its selection.

The sensor allows a more flexible environment, because of its small size it can be placed in more complicated areas with difficult reach. And because it does not use electricity and is immune to EMI, it can be located in high-risk areas, without the uncertainty of being a dangerous material.

2.3.2 Optical Sensor Types

A huge volume of physical magnitudes can be measured. At a first approach, fiber-optic sensors can be classified into the following list, depending on the magnitude to be measured [8].

- Mechanical measurements: this includes displacement, velocity, acceleration, mechanical force, rotation, bending and pressure. Optical effects produced by seismic masses, beams and laser velocimetry are examples of techniques for the measurement of these magnitudes [12].

- Thermal measurements: the temperature magnitude is measured through different transducer mechanisms such as variations in the spectral emission, absorption, refractive index variation, fiber transmission parameters, central wavelength variations in FBGs or due to non-linear effects in photonic materials [13].

- Electromagnetic measurements: physical electromagnetic magnitudes such as electric fields, voltage, electric current and magnetic fields can be measured due to electro-optical effects and magnetic-optical effects produced in photonic materials and devices [14].

- Radiation measurement: in which X-rays and nuclear radiations can be basically detected through luminescence or fluorescence effects [15].

- Chemical measurements: in which the chemical composition surrounding the fiber-optic sensor allows measurement in physical magnitudes such as absorption, luminescence, etc. [16].

- Flow, turbulence and liquid level measurements: through absorption, reflection and scattering measurements produce by liquid flow or turbulences in liquids [17].

- Biomedical measurements: usual physical magnitudes could be acidity, oxygen blood-levels, blood pressure, DNA identification and temperature monitoring [18].

According to the spatial distribution of the measured the fiber optic can be one of the following types:

- Point sensors: when the measurement is carried out at discrete points accessed by different channels [19].

- Distributed sensors: they can measure the value of the state of the measured along a line of space to be measured with a given spatial resolution allowing the determination of the value of the measured in a continuous way at each point of the measurement space, i.e. distributed. When these distributed sensors determine both the level with a specific accuracy and precision, and the spatial position, with a specific spatial resolution they permit the realization of "spatial mapping" of the measured [20].

- Quasi-distributed sensor: they measure the value of the state of the measurand at discrete points of the space situated in a single optical channel being possible to increase the number of measurement points using optical multiplexing techniques. [21]

According to the nature of the transducing mechanism, they can be:

- Intrinsic sensors: the optical waveguide is used to carry out the transduction by modifying its intrinsic characteristics of transmission or reflection depending on the magnitude to be measured. The luminous radiation remains totally or partially within the waveguide [22].

- Extrinsic sensors: interaction between light and the measurand is produced in an external optical device and the modulated light, optically codified, returns to the remote processing unit, i.e. the light modulation process is carried out outside the optical waveguide [23].

According to the type of modulation to be used for the modulation of the optical radiation, the fiber-optic sensor can be classified:

- Intensity modulated sensors: the magnitude to be measured modifies the optical intensity transmitted by the fiber, Such type of modulation allows the use of low cost light sources along with simple optical components, giving rise to sensors which are technically and costly competitive with commercial potential [24].

- Interferometric sensors: the measurand causes a modulation in phase of the luminous radiation in the transducer. It requires coherent light sources, singlemode fibers and complex optical devices to control the polarization. These sensors offer the greatest sensitivity that can be reached [25]

- Polarimetric sensors: the measurand modulates the polarization of the propagating light [26].

- Spectroscopic sensor: the measurand modulates the measured spectrum of optical radiation [27].

The main features of the fiber sensors compared to other ones include their high bandwidth and transmission velocity, with a robust methodology that makes it ideal for working under hostile circumstances and makes it reliable. It has low signal attenuation that allows long communications; this means the power the light signal has entering the fiber is greater than the one exiting. There are different reasons for this attenuation depending on the physical properties of the fiber. The curvature the fiber is summited to generate this attenuation, and the losses are negligible up to a critic point where the light rays finally escape the nucleus because the maximum reflection angle is surpassed. Hence he curvature limits the losses modifying its mechanical parameters. The figure 2.3 illustrates the typical losses on the optical fibers.

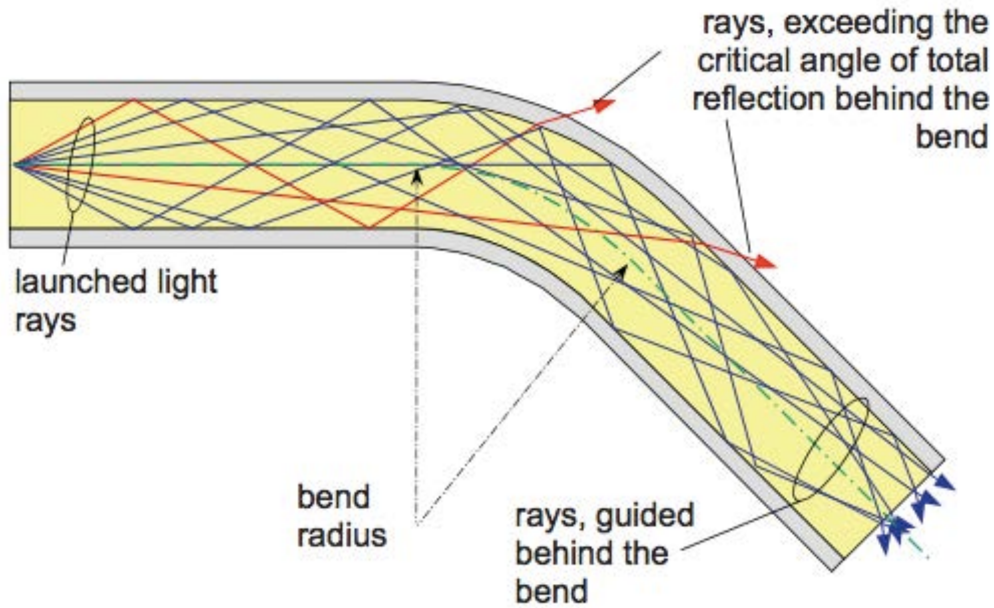

Figure 2.3. Loss at fiber bends [28]

Physically the fiber has small diameter compared to most cables. Mainly polymers compose the plastic fiber, which makes it flexible and mobile, allowing to nicely curving them because of their less rigid structure. It is composed of three concentric cylinders: the core, cladding and coating, respectively from smallest to largest.

The core is where the light travels through following the total internal reflection (TIR) principle [28]. The coating works as a protective backing, being the most superficial layer of the fiber.

The fiber used as a sensor works with optical units. This means that in order to use this sensor in the project it is necessary to use adaptation circuits or optoelectronic stages/devices that transform the electrical signals of the circuit into optical counterparts, able to travel throughout the fiber, and vice versa. These adaptation circuits are called emitter driver and receiver driver, respectively. The first will take the current signals from the circuit and convert it into optical ones using an optoelectronic source, mostly a Light-Emitting Diode (LED) or a laser. The optical fiber may be coupled to this optical source. The light then travels through the fiber and reaches the second circuit, connected at the fiber end by means of a photo receiver. The receiver circuit will contain a photodiode/phototransistor that will absorb the light received and convert it into an electrical current directly related to the targeted physical magnitude to be sensed.

The figure 2.4 represents the three main components of the sensor system.

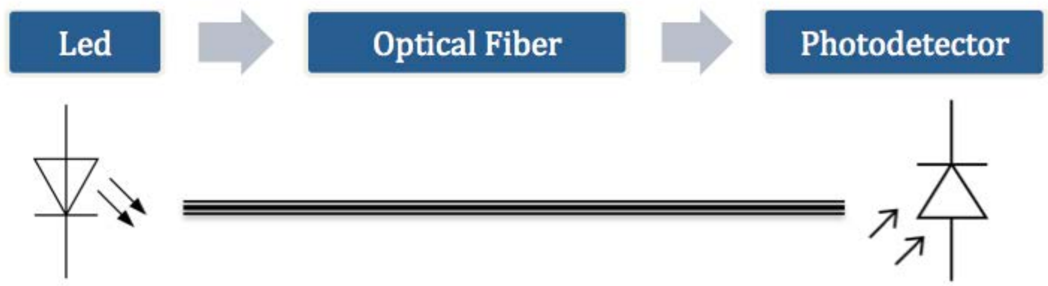

Figure 2.4. Sensor system

The field of temperature sensors covers a high percentage of today´s world sensor market due to the large number of applications in which it is necessary to measure temperature. Because this project is working inside the atmosphere of a transformer, it is the ideal choice for a sensor, avoiding the interferences and adapting to the environment. The measurement will be done studying the variation of the output signal when modifying the temperature it is submitted to.

2.3.3 Light Intensity modulation techniques

The most common modulation approaches for intensity-based sensors are described.

The light modulation is one the techniques of fiber-optic intensity sensors modulation. They are based on the relative displaced between two fibers, determined by the sensing head and depending on the variation of the optical intensity received.

This type of modulation is also used with reflective mechanisms, where the light is launched into an optical fiber, through a reflective surface, into the same fiber or several others. This forms a fiber-optic bundle, which results depend on the reflective-surface distance with regards to the emitter fiber.
It is possible to determine the reflective-surface relative position based on the intensity of the light received. This approached is employed especially for monitoring liquid levels, generally in tanks. The light attenuation depends on the distance from the sensor head to the liquid surface.

A different mechanism for the intensity of the light modulations is by using a bend radius fiber greater than the critical angle. This local bending of the fiber

causes an intensity modulation of light propagating through an optical fiber. The propagating light will generate optical losses by light coupling into cladding nodes, depending on the characteristics of the surrounding media of the region.
For evaluation of the different physical magnitudes it is possible to use spectral measurements. This measurands concern to the external media providing high versatility for the intensity based sensors.

The propagating light beam is confinement into a region of the fiber core, and the power transfer from two closely placed fiber cores can be used to produce a series of fiber sensors based on evanescence field effects, called Frustrated Total Internal Reflection (FTIR) or Attenuated Total Reflection (ATR). FTIR approach takes advantage of a moving medium close to the guiding layer in which the reflection at the boundary can be controlled, thus modulating the guiding properties of the optical fiber and, therefore, the transmitted power. The light at the boundaries has as an effect evanescent fields with a refractive index change. This means part of the electromagnetic fields "enters" the other side of the boundary. This happens for optical fibers in which the light is guided by the inner medium refractive index (core) but a small percentage of the field travels in the cladding. If removing this cladding, the guided light can modify the properties, interacting with the measurand, providing a basis for many sensing schemes. The biggest disadvantage of the field sensor is the weak interaction with the measurand due to the small excursion of the field into the cladding. The field's strength decreases in an exponential way outside the core regardless of the waveguide shape or the modal distribution. This means the architecture for this transducer is made of a segment of optical fiber with the cladding removed or side-polished [8].

The intensity sensor proposed in this project uses a macro-bending structure. It is based on a curved multimode optical fiber. The numerical aperture, which is temperature dependent, changes on the bent optical fiber. The thermo-optic coefficients depend on the materials. The advantage of using a plastically fiber is the large diameters of the former, making the sensor less fragile and easier to handle, reducing development and maintenance cost. [29]. A commercial step index fiber with a good tensile strength and flexing is used. These characteristics provide good mechanical properties at the time of manufacturing the sensor. From the middle section of the fiber length, the buffer coating is partially stripped. The length of this stripped section is about 30mm. The fiber sensor is formed by creating a single 180º loop with a concrete bend radius [30].

The importance of the appropriate selection of wavelength means chemical species (in liquid and gas form) can be directly detected through the absorption of the evanescent field.

Other modulation techniques take advantage of spectrally based fiber optic sensors, which depend on a light beam being modulated in wavelength by an environmental effect. Examples of these types of sensors include those based on blackbody, fluorescence, absorption, etc.

2.4 TEMPERATURE SENSORS APPLICATION: TRANSFORMERS

The purpose of the project is to develop a sensing scheme capable of measuring the temperature inside of a power transformer, and then transmitting the information wirelessly to an interface in the computer. To create the most optimized sensor, first it was necessary to understand the transformer, which due to its features limits the selection of the electronic components.

A transformer is a device used in electric power systems. Its main goal is to convert the current or voltage into energy, maintaining the power constant. In order to do so, the machine uses electromagnetic induction to transfer energy between several circuits. When the transformer is used for the energy distribution it is referred to as a power transformer [31], usually rated at 500kVA and above. The selection of the transformer depends on the application. The average life of a power transformer is around 20-35 years [32], but as transformers age, the risk of failure increases as the internal condition degrades. The failures [33], [34] can be categorized as mechanical, electrical or thermal, and caused externally (severe conditions on the apparatus, such as lighting strikes), or internally. One of the main internal causes is the insulation deterioration; the transformer is composed by two active components, usually immersed in oil: the windings and the magnetic core. The losses in these components generate heat, which must be properly evacuated towards the environment in order to avoid high temperatures and overheating, which will speed up degradation of the winding insulation and in consequence the entire transformer.

The transformers are usually reliable sources, with a failure rate of 0.77% [35] but because the consequences could be fatal to the operators, the environment and generate high cost, the monitor and diagnosis of the machine are essential.

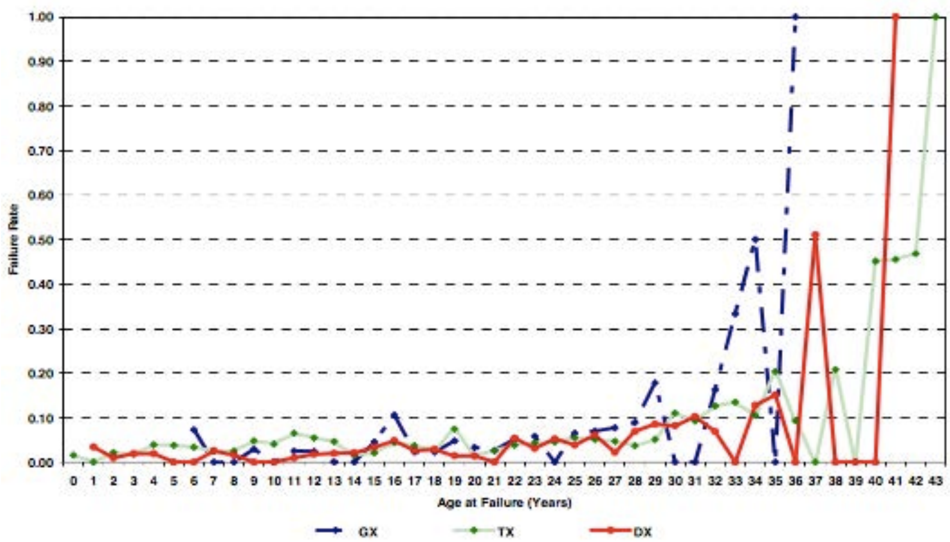

Figure 2.5. Performance with age of a GSU (Generator step-up) (Gx), transmission (Tx) and distribution transformer (Dx) [35]

Figure 2.5 illustrates how failures increase as years go by, proving the degradation of the insulation strength, unable to withstand system event, and the wear out and general ageing of components. The deficiency of the transformer in the early years of its life is normally caused by design or manufacturing causes.

The biggest preventive measure of failure is to control the most influential parameters. Monitoring the temperature [36] allows to estimate the loss of life caused by the overheating.

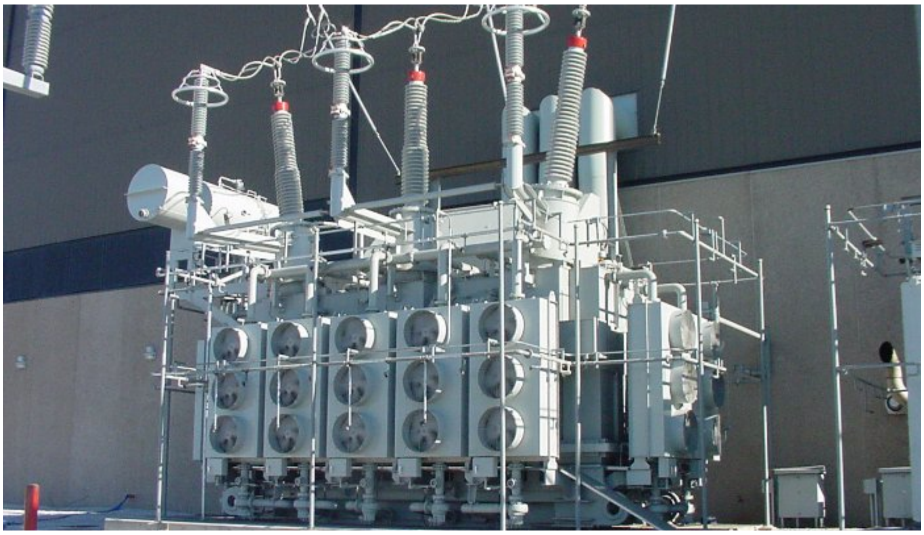

Figure 2.6. Electrical transformer for power plants [37]

Fig 2.6 is an image of a typical power industrial transformer. The interior of a transformer is composed by different sectors with different temperatures. The hottest regions are referred to as hot spots, usually located in the top area of the windings. The temperature in these hot spots is the main factor to determine the useful life when working with the electric charge, becoming an important parameter when analyzing the transformer longevity and the aging of the insulator components

The method used in this project uses fiber optic sensors to monitor the temperature at a specific spatial location. The sensor should have the capacity of measuring the whole temperature range the transformers can encounter while not being affected by electromagnetic or radiofrequency interferences, caused by the transformer and the wireless communication respectively. The sensor and/or cable should be insulated, which will allow introducing it directly at the hot spot, allowing the placement in difficult locations with a simple installation.

The final goal of temperature monitoring within a transformer is the early diagnosis and anticipation of possible failures. The temperature evolution and its trends inside it have resulted as a useful degradation indicator to control and prevent overheating. This is why the presented project will focus on designing a remotely controlled instrumentation temperature sensor capable of transmitting the data wirelessly, creating a safer environment for the worker.

Chapter 3

WIRELESS COMMUNICATION

In order to measure the temperature inside of a transformer, this project proposes the use of an instrumentation systems based on an optical sensor. The aim is the temperature data acquisition and its transmission to the control unit. The importance of measuring the temperature in these machines was previously explained in *Chapter 2.4 Temperature Sensors Applications: Transformers*, but it can be summarized in increasing the effective working period and reducing the risks of failure.

Along with these failure risks, working with industrial components such as these ones that work with great amounts of energy can make it dangerous to get close to them while being operative. This hardens the possible way of getting the information of the transformer status. The small size of the sensor allows locating it in the inside. Moreover the user in charge of maintenance may remotely acquire the information in the control unit using a wireless transmission system.

The wireless communications uses modulated electromagnetic waves that travel through space. The transmission works between at least two points, an emitter and a receiver, but depending on the protocol this connection can be up to hundreds of nodes. The only physical objects composing these models are the devices that transmit and receive the signals with the data, an ordinary example of these are the common TV antennas.

The main advantage of the wireless communication is the no need for cables, but it also assures a fast, easy and clean installation. Less wires means less complexity. The communication points are referred to as nodes, and are able to compose large flexible networks and quick in response.

The mode of communication is set by the selected protocol. These protocols work with a common goal, the remote transmission, but have different characteristics depending on the application wanted. The main features that difference the protocols are:

- Frequency range
- Speed rate
- Scope

Nowadays there are three main protocol systems where wireless sensor networks may be deployed: Bluetooth, Wi-Fi and ZigBee. These three will be explained in detail within this chapter. This analysis will focus on the characteristics and the contribution each can have on the project, as well as on the final decision for the designed system.

3.1 BLUETOOTH

Bluetooth is a technological specification for wireless networks that allows voice and data transmission between different devices though a safe radiofrequency. This technology permits communication without connectors or cables and the possibility of creating domestic nets to synchronize and share information that is stored in different equipment.

One of the most common situations that uses of this technology is when people in the same place exchange, normally pictures, with their respective mobile phones. The devices connect with each other and then the transfer is carried out.

Figure 3.1. Bluetooth logo [38]

The term Bluetooth is the commercial and most popular denomination of the standard wireless communication IEEE 802.15.1. The first business that investigated this technology was Ericsson, in charge of the leading the association of business that was later created and included IBM, Nokia, Microsoft and Motorola among others.

The commissioning of this standard is the lowest when compared to the other models (Wi-Fi or ZigBee). The start up depends on the number of components in the network, and is limited by a maximum distance between them.

There are three types of Bluetooth's modes, depending on the scope permitted between the connecting devices [38]:

- Class 1: 100 meters.
- Class 2:10 meters, and is the most frequent used in nowadays society.
- Class 3: 1 meter.

The hardware of the Bluetooth system can be divided in two parts. The first one is the radio device that modulates and emits the signal. The second one is the digital controller: a digital signal processor known as Link Controller, along with a CPU and interface processor.

The main features of the standard Bluetooth are [38]:

- *Frequency range*: 2,4-2,484 GHz
- *Speed rate*: 3 Mbps
- *Scope range*: 10 meters

The communication is established with a frequency hopping mechanism (FHSS); it proves multiple frequencies until finding one that works properly. This mechanism avoids interference in difficult environments.
Out of the three main protocols Bluetooth is the less reliable of all, especially when working with networks with more than two devices. An advantage of the system is the encrypted system integrated, but it is only used with data by default and depending on the size of the exchange.

For this project, the scope range sets a limitation that discards the Bluetooth as an option. Also, the environment in which the project will be carried out forces the use of a rougher technology, able to stand hostile situations.

3.2 Wi-Fi

Wi-Fi is the commercial brand of Wi-Fi Alliance, an organization that adopts and certifies that the equipment meets the standards 802.11 of wireless networks in local areas. Wi-Fi Alliance was known as WECA (Wireless Ethernet Compatibility Alliance) until 2003.

Figure 3.2. Wi-Fi logo [39]

The objective of the brand is to promote the wireless communications and to ease the compatibility of different equipment. All the products with Wi-Fi connection have an interoperability certified, which makes it one of the most popular standards nowadays. But this massive growth of use threatens the availability of radio-electric spectrum, especially when the connections are done with over 100 meters of distance. When increasing the distance, the risk of interferences increases as well.

Wi-Fi standards are used to create networks that require uninterrupted activity of the devices. The connection methodology uses one access point, referred to as hot-spot or remote emitters, that connects with the components of the net, the routers, which receive the information emitted and the reception devices (USB, PCI, PCMCIA). These last components have unlimited numbers in the network of the standard through the use of signal repeaters.

The main features of Wi-Fi standard are [39]:

- *Frequency range*: 2,4 GHz
- *Speed rate*: 54 Mbps
- *Scope range*: 80 meters (open field)

Wi-Fi has a greater hardness than Bluetooth, making it a more reliable transmission system. It includes a robust identification system, but one of the biggest inconvenient of this technology is its low security. The easy installment makes it a frequent used net, but with tendency of leaving it open, without any protection over the information that circulate through it. There exist encryption protocols that allow codding the data transmission and guarantee the confidentiality.

The use of Wi-Fi has increased considerably over the last years; users are adopting the technology in all levels everywhere around the world. But as any technology, it has pros and cons.

The biggest advantage this technology has is the absence of wires, capable of joining unlimited number of devices with multiple characteristics, avoiding the need of different connectors depending on the machine the user uses. The easy connection to the network makes it the selected protocol for the Internet around the globe.

However, it also has its disadvantages. The connection quality is limited of multiple factors, such as the electromagnetic radiation generated by home appliances, which directly affect the transmission speed. It is also not fully compatible with some nowadays devices of different brands affecting the velocity as well, despite its global standardization.

It has an initial limited scope, which makes it ideal for domestic uses. However, it is true that the same router offers a more stable connection and with greater reach in open spaces than inside houses, based on the interferences previously mentioned.

The frequent use and growth of the technology means an increase in the connection points globally, but the closeness between two hot-spots affects the communication quality.

3.3 ZIGBEE

ZigBee is a specification of mesh network for wireless local nets of low power that cover large areas. It is being designed to provide high performance of data communication in applications with low working cycle and a required low consumption. It is frequently use for industrial automatizing and in the operation of physical plants.

Figure 3.3. ZigBee logo [40]

It is based on the specification 802.15 of the Standard Association Institute, operating under the radio physical specification of 802.15.4 and in the radio frequency bands with no license. These specifications are hold and updated by the ZigBee Alliance. This organization has over seventy members, with five leaders called promoters that are Honeywell, Invensys, Mitsubishi, Motorola, Phillips and Samsung [40].

The standards created by the alliance allow the creation of multivendor interoperable offerings. The manufacture of custom applications does not need to operate with others manufacturers applications, and the users are free to design their own modality, with their own variations and extensions.

The mesh works in local areas (LAN), wireless local areas (WLAN) or virtual local areas (VLAN) networks employing this methodology. It can either be a full or partial mesh. When each node of the network is directly connected to the other ones is a full mesh, while a partial mesh has nodes connected between all the others, and some nodes connected only to the ones they transfer the most data with. This last modality reduces the consumption and allows a more efficient system, establishing the communication when needed.

This protocol was designed for a smaller information transfer and local use in adverse environments, with the main focus of a fast start up. It supports lower data rates and uses the mesh networking protocol to avoid hub devices and create a self-healing architecture. It is thought for a global and open use on reliable products with low cost, low consumption and reduced space.

The values that identify the standard features of the system are [40]:

- *Frequency range*: 2405-2480 MHz
- *Speed rate*: 540 kbps
- *Scope range*: 100 meters (open fields)

This mentioned values are the standard for a ZigBee net, but the specifications vary depending in the country. In North America it can operate in two different free bands: 2.4 GHz and 915 MHz. While in Europe it is 868 MHz. When working with 2.4 GHz the user has up to 16 channels and a data rate of 250 kbps. With 915 MHz the channels are reduced to 10 and the rate to 40 kbps. In Europe with only one band, there is 1 channel and a rate of 20 kbps.

One of the main characteristic of ZigBee is its fast commissioning and start up; less than 30 ms. The purpose of this is to assure that the sensors and actuators are activated immediately without any incidences on the net, giving the protocol a robust character ideal for hostile situations.

Its design and construction makes it the roughest protocol, able to work on industrial environments and ideal for sensors, lighting, security and more appliances. It has a hard intrinsic encryption in comparison to the data exchange, a variety of features to ensure exceedingly reliable operations. Including quality assessment, clear channel assessment and receiver energy detection.

The transmitting distances that can be reached from one station extend up to 100 meters, although longer distances can be achieved relying data from one node to the next one.

This communication is a solution for the automation, designed specifically for it with its main features being the low consumption, the mesh net typology and the easy integration, with a high connection flexibility and security against failures.

The data transmission is done with packets, with a maximum of 128 bytes. Compared to the other protocols it is the smallest one, but the common application of this protocol does not require high data rates [41].

The addresses for this standard can either be of 64 or 16 bits. The longest address, 64 bits, identifies each device uniquely like each device has its own IP address. When using the 16 bits addressing it uses only one channel, and control up to 65536 devices in the same network. In this case, the user configuring it may set the address name for the devices.

The hardware of ZigBee has been designed for a low cost in scale production, using mostly digital circuits for the radio configuration. The material from which the radio comes set the radiofrequency characteristics. The standard technology is based on nodes with integrated sensors that carry out the monitoring tasks assigned. The multiple nodes communicate with one another, transferring the acquired data to the node set as control unit in charge of registering the received information and react when needed. This reaction frequently means activating the actuators.

One of the greatest features of the ZigBee standard is the ability of the nodes to automatically organize their communication routes and finding the optimized path by themselves which leads to very flexible and easily editable networking topologies. The user may alter the network when needed, and the already established nodes will automatically adapt to those changes.

The ZigBee protocol has a temperature range for operation ranging from -40ºC to 85ºC, and has three different network topologies with different characteristics that make the system adaptable to the required situation.

The network distribution topologies are [42]:

1. Star: presents a long useful life as a consequence of the low consumption required. It is commonly used because of its great advantage of simplicity. The configuration forms a star without outlying nodes communicating with a central node. The coordinator has the primary control, and the end devices monitor their applications and report them to the coordinator.

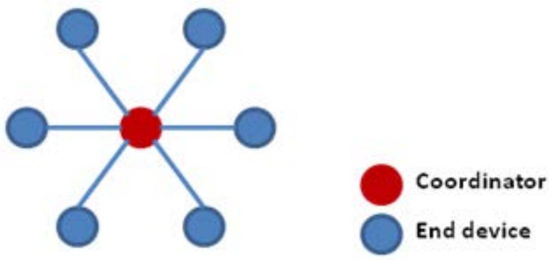

Figure 3.4. Star network distribution [42]

2. Mesh: in which there are multiple paths for a destiny, obtaining a high reliability. It consists of multiple nodes located as needed with a range that capacitates them to communicate with each other to form a mesh. The path the messaging follows across the network can be routed using different stations as relays. The multiple route choices make it the most robust typology, avoiding interferences by selecting a different path instead. The coordinator and all the end devices communicate all with each other. It allows a more complex network formation.

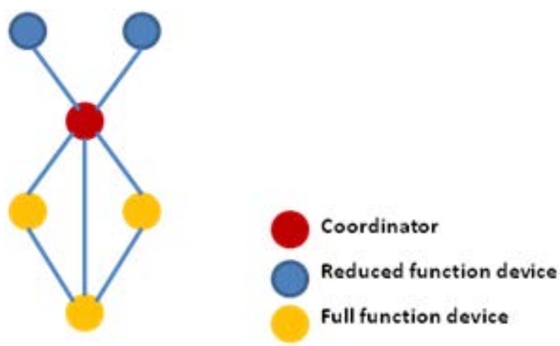

Figure 3.5. Mesh network distribution [42]

3. Cluster Tree: this topology combines the two previous ones, Mesh and Star, obtaining the benefits from both. Several small clusters, a small selection of a bigger network, are present and enable to communicate with each other. A single coordinator may control the clusters, or each cluster can have its own individual coordinator that is able to communicated with the other ones. It is possible to choose one of these clusters coordinators to control the rest.

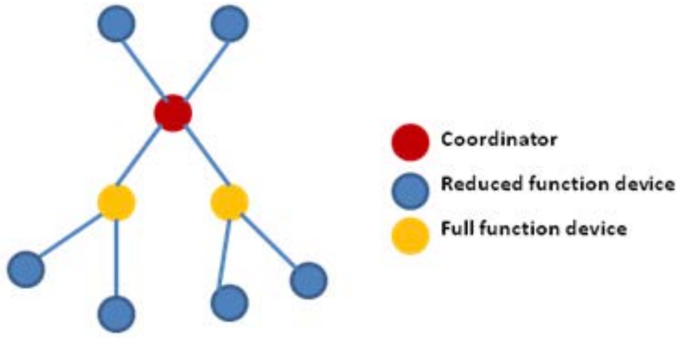

Figure 3.6. Tree network distribution [42]

The nodes do not need to be continually emitting, and can be set to work for a determined period of time, or even take samples every once in a while, entering a stand-by mode when is not being used. The low power device has enable battery life to be measured in years, enabling the network to not require constant maintenance. This reduces the node consumption, and extends the active life of the devices.

From the previous figures 3.4, 3.5 and 3.6 we can observe different types of devices in a ZigBee network. These are:

- Coordinator (ZC): the most complete type. It is in charge of controlling and monitoring the established the network and the transmission paths, the communication channels that the rest of the devices must follow to connect between one another. There is only one coordinator per net, storing the network information and repository of the security keys. It may also work as a router in the net. There are two coordinator types based on its operation scope.
  - The PAN (Personal Area Network)- coordinator that acts as coordinator for the entire net.
  - Ordinary coordinator that works within the scope of the cluster.

- Router (ZR): interconnects the separated devices in the network typology, and offers an application that permits the user code execution, an application level inside the protocols. It is an optional device for the mesh, and has to compulsory been associated with a coordinator to belong to the network. It can also be in charge of the message routing, and can act as an intermediate router passing data on from other devices.

- End Device (ZED): it has the functionality of communicating with the coordinator node but cannot transfer information to other devices, which means it cannot be associated with each other. Does not participate in the message routing and has low memory requirements, which makes the cheapest device. Usually works with sensors that acquire the data. It has a low consumption due to the capability of using a "sleep mode" that activates the device only when required, increasing the efficiency and the batteries life. It has two different functionality types:

  - Full function device (FFD): known as active node. It can receive messages on the 802.15.4 format. Along with the end device capacity it can also work as a PAN coordinator, coordinator or a router in the network.
  - Reduced function device (RFD): known as passive node. The capacity and functionality are limited by the standard, with the objective of achieving low cost and great simplicity. These are normally the sensors and actuators of the network. It can only work as end device and can only communicate with the coordinator. The coordinator receiver status of the device it's monitoring regularly.

Comparing the ZigBee standard to the other communication protocols, it can be observed that this technology has been optimized to ensure that it meets the intended requirements of the other protocols, such as Bluetooth and the like, fulfilling the needs for remote control and sensing applications.

This means the most suitable choice for this project is the ZigBee protocol. The purpose is to remotely obtain the information from the designed sensor. Because the final goal is the placement on the sensor on a hostile environment, the roughness of ZigBee is ideal for it. Its 100 meters range allows more than enough safe distance, and allows flexibility for the sensor. The fast commissioning makes the monitoring process more reliable, and the limited frequency is not an obstacle because it covers the size needed for the data transmission. The biggest downside of this technology is the low transmission velocity, but the proposed sensing application will be working with low quantities of data, which means the velocity available is more than enough for this project.

The incorporation of this protocol to the project will be done with XBee antenna modules attached to the Arduino One plates.

3.3.1 XBee Modules

XBee is the commercial name of radio frequency communications modules made by the DIGI industry [43]. DIGI International is an industry based on the modem development of connection of wireless nets. The MaxStream industry belongs to DIGI, and it has wireless modem modules, radio independent modems, radiofrequency design services and adequate software to manipulate them.
It is based on the ZigBee communication protocol, and even though there are some that are configured by the manufacturer most modules use the net protocol standard IEEE 802.15.4.

The XBee modules have been designed for applications that require high data traffic, low laitance and predictable communication synchronization. These needs are fulfilled with the ZigBee features, so that is why the XBee are based on this protocol. The modules are wireless devices easy to use [43].

There are two main modules: regular and PRO, having the latter a longer scope range, around 1,6 km, but also has a higher power consumption. The hardware difference between them is the size of the chip, with the PRO module being longer than the regular.

The modules are small chips capable of communicating wirelessly one with another. There are integrated solutions for a wirelessly intercommunication and communication between devices.

From the IEEE 802.15.4 standard the XBee modules work with a 2,4 GHz range and 100 meters scope reach on open field. The sensitivity of the receivers has a low value of -92 dB, reducing the consumption of energy and providing a greater reach.

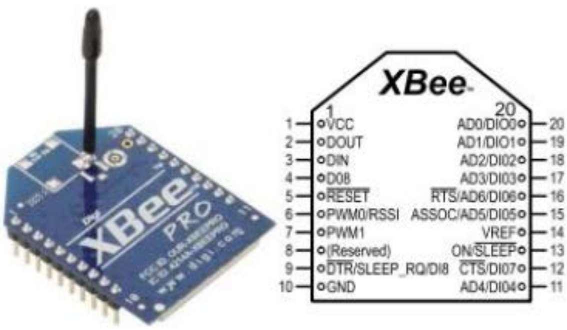

Figure 3.7. XBee Pro module [44]

The hardware of the modules can be observed in the figure 3.7 and works as antennas for the transmission. There are different types of antennas [45]:

- Chip antenna: a small and flat ceramic chip that works as the antenna. It is fast, simple and cheap. It is robust, but the signal is attenuated in a lot of directions. The most frequent use is when there is a small place to locate it.

- Wire antenna: a small cable that sticks out. The maximum transmission distance is the same in all directions.
- u.FL / RP SMA (RP type of connector subminiature version A) antenna: both types have a small connector for an external antenna. These modules are designed for situations that require a special antenna or to place it in different locations. The only difference between them is the size of the connector.
- PCB antenna: the antenna is printed on the XBee plate.

The pins observed in the figure 3.7 require minimal connections. It is powered at 3,3 V, unlike the Arduino plate which needs 5V. However when connecting the modules, the XBee adapts to the Arduino 3,3V pin and uses it as source.

The XBee modules have to be configured before their use. The working mode has to be set; the different types will be later explained on this chapter. In order to do this configuration DIGI offers a free software tool called XCTU [46] that allows to simply setting the firmware of the modules. The modules can create a mesh network, for which each device will be addressed using again the XCTU software.

The configuration is done with a serial communication between the computer and the XBee. Like in the ZigBee protocol, XBee has two addressing modes: it may either use 16 or 64 bits. The greater number allows the connection of more devices to the network ($2^{64} = 1{,}84 \cdot 10^{19}$), but the addresses of the devices cannot be defined randomly by the user and are set before its use. When working with 16 bits the programmer may set the address of each component, using the MY command in XCTU [45].

The device types are the same as in the ZigBee standard with a coordinator, router and end device, but as an improvement XBee allows more operation modes, as previously mentioned, which are the following:

- Receive/Transmit Mode: Both modes are defined the same way. The XBee is positioned in this mode when the antenna is working through the radio frequency, either sending or receiving the data. When using the direct mode information gets sent immediately to the destiny module. In an indirect mode the data is held in the module for a period of time and gets sent only when the destiny address requires it. Additionally it is possible to send the information using unicast or broadcast. The first modality is a point-to-point communication, and the only one that receives an answer from the destiny address. This answer is internal, so the user is not able to see it. The broadcast mode the communication is established from one point to all the nodes that compose the network.

- Sleep Mode: This is the stage the XBee reaches a low consumption state when it is not active. These modes are disabled by default, remaining in a resting or reception state, but always ready to answer to a command. The configuration of this command is established with the SM command in the XCTU software.

- Command Mode: This mode allows integrating AT commands to the XBee module, in order to modify or configure parameters. To be able to enter the commands it is necessary to use the XCTU software.

- Transparent mode: in this mode all the data enter through the pin 3 in the module, is safe to an input buffer and the transmitted. Everything that enters as a radiofrequency package is saved to the output buffer and then sends by pin 2. This mode is oriented for point-to-point communications, where there is no control need. It is the simplest available configuration.

- API: it is the most complex method. It allows the use of head frames that assure the delivery of the data. It extents the possibility of interaction between the application and user. All the information entering and leaving the module is packed in frames that define operations and events inside the module. It provides alternatives for the module configuration and routing of the information in the user application. It allows the mode to automatically modify the addresses instead of using the command mode. The operations this mode permits are:

    - Transmit data to multiple destinations, without using the command mode.
    - Receive the state of the transmitted information (received/failed).
    - Identify the origin address of each received packet.

- Idle Mode: When the device is not in any of the other modes. It is not receiving or transmitting data, the RF modem is in Idle Mode. The modem shifts into the other modes of operation under the following conditions:
    - Transmit Mode (Serial data is received in the DI Buffer)
    - Receive Mode (Valid RF data is received through the antenna)
    - Sleep Mode (Sleep Mode condition is met)

The configuration process includes the typology the network will follow [47]:

- Point-to-point: the ideal communication to replace the serial communication with cable. It uses the XCTU commands MY and DL. The purpose is to randomly define an address for the module using the MY command, which is going to communicate with a different one with address DL, also randomly defined. In this mode the receptor module sends a package to the origin one indicating that the data was correctly received. In order to establish this communication, the modules have to be in the same channel (CH) and the same network (ID).

Figure 3.8. Point-to-point communication configuration [47]

- Point- to- multipoint: In this model the module can communicate with one or multiple modules located in the same network. It offers more security to the network than the broadcast mode, because it needs the modules addresses to communicate. The communication uses the MY and DL commands like the point-to-point typology, but will require two more commands. The first one is the ID of the PAN. All the modules with the same PAN ID will belong to the same network. The ID command is used to establish the value of the PAN, with a range from 0x0 to 0xFFFF in hexadecimal format, because the configuration of point-to-multipoint uses 16 bits for addressing. The other command is CH and corresponds to the assignation of the channel by which the modules are going to communicate. There are 16 channels available, establish by the standard IEEE 802.15.4.
  Each module has a different MY address, but the same CH and ID. This mode allows a more control communication, because in order to perform the transmission all the module address must be known.
  This connection uses a central node as coordinator and the rest of the nodes as end devices connect it to the coordinator.
    - Coordinator: is the central node of the net. Initializes the network and allows other devices to connect. It can select the channel frequency and the net synchronization. In order to establish it as coordinator the command CE (command enables) has to be set as 1.
    - End device: is a remote node of the network. It communicates with the coordinator and other end devices and can to Sleep Mode.

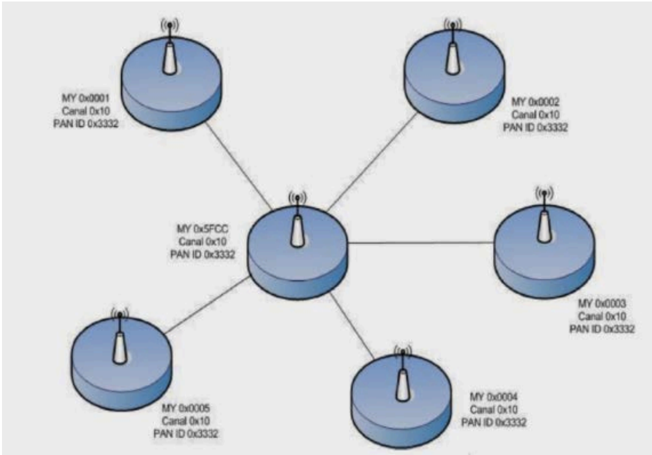

Figure 3.9. Point-to-multipoint communication configuration [47]

- Broadcast: allows sending the information from a node to multiple nodes on the same network, but the information is the same to all of them. The configuration of the modules requires a broadcast address, so any module receiving the data from broadcast address destiny must accept it. This address is:

  DL: 0x0000FFFF
  DH: 0x00000000

  This address is configured in all the nodes of the network, for both types 16 or 64 bits.

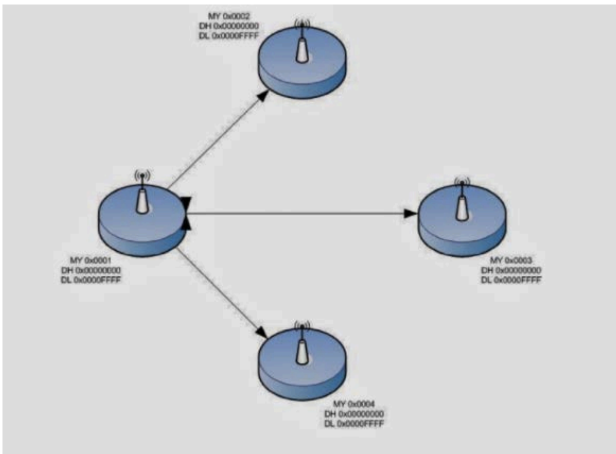

Figure 3.10. Broadcast communication configuration [47]

- Peer-to-peer: allows all the modules to connect with each other. It creates a connection pair by par through the entire network. Each module has to be set as master/ slave. The non-beacon configuration is the default configuration of the peer-to-peer. All the nodes are constantly activated, so the devices connecting to the network have to be set in the sleep mode, and only get activated when it is necessary the data transmission. The routers of the network are also in a sleep mode and in a time interval send existence signals to the rest of the network. For the communication the devices have to be clearly organized, to guarantee the signal in the process. This typology has an energy saving advantage, and is frequently use for devices with a secure power source. The beacon connection uses autonomous powering, like external batteries.

3.3.1.1 XBee Shield

The shields are circuit attachable plates to add functionalities to the Arduino. It allows extending the hardware and communicating with the Arduino either through analogical and digital ports, or with buses such as SPI (Serial Peripheral Interface) or series ports. It uses the same powering, with 5V and a ground connection. The shield must have the same factor form as the plate is being attached to, with a concrete pins spacing.

The XBee antennas can be attached to one of these shields to establish the communication between the microprocessor in the Arduino board acquiring the data, which will then be passed on to the antennas for its transmission.

The specific XBee shields allow an Arduino board to communicate wirelessly using ZigBee, based on the XBee module from MaxStream. The communication has a reach of a 100 and 300 meters, inside or outdoors respectively. The connection can use either an USB/serial or command mode configuration, establishing mesh network. It provides female pin headers for use of digital pins 2 to 7 and the entire line of analog pins on the board [48].

The creation of the network uses the XBee technology to establish the nodes composing it, using the addresses of the modules. The shield permits to adapt the communication technology to the sensors, creating a monitoring environment.

The addressing includes the configuration of the commands CH and ID, which for devices in the same network have to have the same value. The destination and origin addresses are set with the MY, DL and DH commands, different for each node in order to establish the data transmission between one another. There are default settings for the communication, and three possible options [48]:

- If a module's DH is 0 and its DL is less than 0xFFFF (i.e. 16 bits), data transmitted by that module will be received by any module who’s 16-bit address MY parameter equals DL.
- If DH is 0 and DL equals 0xFFFF, the module's transmissions will be received by all modules.
- If DH is non-zero or DL is greater than 0xFFFF, the transmission will only be received by the module whose serial number equals the transmitting module's destination address.

The XBee shield can communicate two different ways, in order to establish the mode it uses two jumpers located on the shield. These jumpers are small removable plastic sleeves that fit into the two of the three external pins called XBee/ USB. The difference between these modes is to what the XBee is connected to: either the microcontroller on the Arduino board, or the USB serial chip on the board [49].

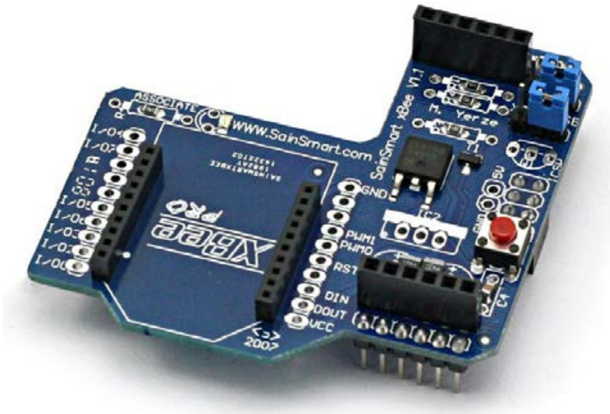

Figure 3.11. XBee shield board [49]

- The XBee position: the hardware in this case covers with the jumpers the two pins towards the interior of the board. This means the DOUT pin in the XBee is connected to the RX pin of the microcontroller and the DIN to the TX, of the same components respectively. The RX and TX pins of the microcontroller are connected to the TX and RX pins of the FTDI chip respectively. This means the data sent from the microcontroller is transmitted to the computer through the USB and being also sent wirelessly by the XBee module. This mode disables the microcontroller, which will only be able to receive data from the XBee module and not from the computer through the USB,
- The USB position: enable with the two pins nearest the edge of the board covered by the jumper. The DOUT pin of the XBee module is connected to the RX pin of the FTDI chip, and DIN on the XBee module is connected to the TX pin of the FTDI chip. This way the XBee is able to communicate with the computer directly, but is only able to work when the microcontroller has been removed from the Arduino plate. This is because the microcontroller on the board will be able to communicate with the computer through the USB port, but neither one of them will be able to transmit anything to or from the XBee module.

Chapter 4
POWER OVER FIBER

4.1 INTRODUCTION

Optical fiber is a widely used transmission method due to its potential as a high capacity communication channel of light signals. An emerging technology is currently under development where the optical fiber is used to transmit power to a remote station in the form of light energy that is then used to feed an electronic device. This new technology is called Power over Fiber (PoF).

The PoF system consists of a high- power laser diode, a transmission line (the optical fiber) and a photovoltaic (PV) converter. Both the optical fiber and the PV converter are placed inside an exclusion region, where the electric energy provisioning becomes difficult or inaccessible, whereas the light source is located within a problem-free area. The converter stage remotely transforms the received optical power into electricity thus driving an electronic circuit directly. The PV converters are the most suitable devices for this kind of biasing. Limitations of overall system performance mostly depend on the efficiencies of the transmission medium and the PV converters [50].

The use of this technology has diversified into multiple fields of application such as remote feeding, communication antennas, vision systems, etc. In the case of PoF systems, the use of microelectromechanical systems has the advantage of being able to remotely power the node, giving a greater versatility to the network [51].

It is worth mentioning that the use of PoF technology may lead to additional benefits, such as the capacity of galvanic isolation between the two ends of the fibre, the transmitter and receiver, its immunity to electromagnetic interference (EMI) and its intrinsically safe nature. The latter advantage is of interest in application such as the sensing flammable gases. Additionally, PoFs with their large numerical aperture have acceptable flexibility, relaxed connector tolerance, easy and efficient coupling with high numerical aperture light sources, as well as quick and easy termination procedures. These properties boost the use of the system in applications such as aircraft, engine control… The low attenuation coefficient of standard silica multimode fiber has opened up more recent large network area coverage applications, such as optically powered remote sensor networks and remote powering of antennas in pico-cellular network architectures for radio-over-fiber systems. In contrast, Graded- Index Polymer Optical Fiber shows several advantages over conventional silica multimode optical fiber in short distances thus being more flexible and ductile, making it easier to handle as well as offering potential lower cost associated with its easiness of installation, splicing and connecting. The main limitation of this PoF model is the maximum operating temperature of the PoF material, which is closely related to its quite low glass transition temperature [50].

4.2 SYSTEM IMPLEMENTATION

The PoF system is composed of a high power laser diode, the optical fiber and a photovoltaic cell (PV cell). The PV converter remotely receives the optical power and converts it into power electricity. It has a great efficiency performance and no requirement for any kind of biasing.

When developing this system, it is important to make sure the laser diode wavelength matches the PV converter efficiency and the optical fiber attenuation. It also has to be considered the appropriate level of injected optical power to avoid a phenomenon of fiber fuse, and to control the power dissipation in both cell and receiving element.

The sizing of the cell plays an important role, especially when working with endoscopic applications, which require relatively high efficiencies and miniaturization.

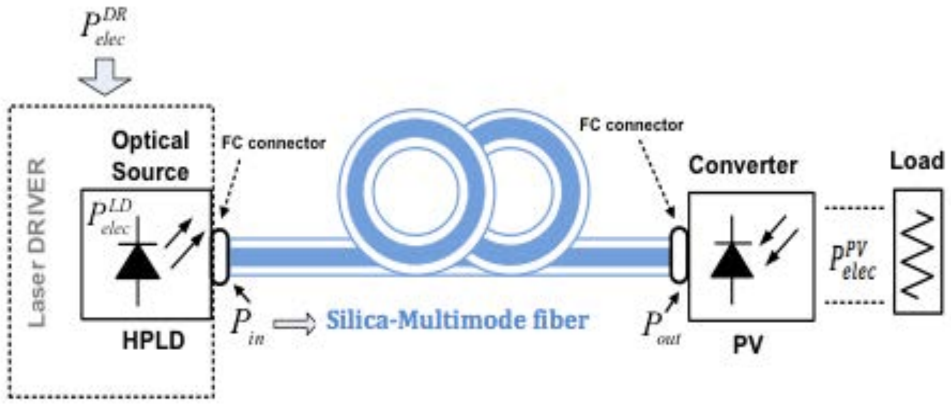

Figure 4.1 Block diagram of generic PoF system [51]

The figure 4.1 provides a visual image of all the elements composing a PoF system:

- Optical Source: the optical source is the high power laser diode. This device is a semiconductor that uses p-n joints similar to LEDs, but with a special configuration that under adequate conditions is able to emit a light that can reach high intensity.

- Photovoltaic cells: is a power system over the optic fiber that composes the receptor. Its function is to convert the luminous energy into electrical. The PV cells used for this application are fabricated with semiconductors capable of transforming the monochromatic light in electrical energy very efficiently. The key to reach this high efficiency values are the correct adjusting between the wavelength of the incident light and the energy of the band of the PV cell.

- Transmission media: the optical fiber is the transmission media formed with a nucleus and a cladding of materials with different refraction indexes, and a total reflection with few losses.

4.3 DEVELOPED SYSTEM

The developed system uses a parallel topology; the selection of the topology is based on the required power for the remote device and the reliability expected from the design to make. This parallel topology is used to increase the output power in the cases that only one Photonic Power Module (PPM) is not enough from the point of view of the power requirements. The diodes are necessary to avoid the inverted current in the Photovoltaic Power Converter (PPC). The diode must have a low direct tension to reduce the voltage drop [52].

The developed system is able to provide optical remote powering of hundreds of mW in DC and pulse mode for different types of multimode silica and polymer optical fibers.

The laser used is of 1.5W @2.2A with a central wavelength of 805nm and with FC connector. At reception the power converter (PV) is located. The designed laser provides a slow start and a current limit to protect the laser. The slow start is controlled by the charging of a capacitor for avoiding rapid changes in the current temperature of the laser diode. Additionally it performs a temperature and a current control loop system to stabilize the output optical power.

One of the main design parameters of the system is the temperature of the laser diode, as the optical emission power strongly depends on temperature. It also affects the laser lifetime. The device dissipates energy in the form of heat depending on the point of operation and this causes an increase in the temperature. This laser diode has been designed at an ambient temperature of 25ºC and 2.2A operation current.

The highest transmission power density has been achieved with 200 µm core diameter multimode silica optical fibers obtaining a maximum coupling efficiency of light injected into the fiber from the laser´s output. The PV cell is optimized for maximum power conversion efficiency at 805 nm wavelength corresponding to the emission wavelength of the laser diode.

From figure 4.1, we define the optical feed power *Pin* as the total effective power launched from the HLPD into the optical fiber. We note *Pout* as the received effective optical power impinging the PV after all transmission losses arising the link, including all connector losses as well as due to the fiber attenuation vs. wavelength characteristics. Around 19dB/km of fiber loss between the transmitter output and receiver input was assumed for the 200um-core diameter multimode optical fiber at the operating wavelength. We define P_{elec}^{DR} as the electrical power consumed by the HLPD driver that includes mainly both the laser diode and a Peltier-based temperature control loop. P_{elec}^{LD} defines the power consumption of the HPLD itself. Finally P_{elec}^{PV} corresponds to the electrical power delivered by the cell after the electrical-to-optical conversion process. The optical power balance of the PoF system can be expressed as:

$$P_{in}(dBm) = P_{out}(dBm) + Att\left(dB\right) \tag{4.1}$$

$$Att\left(dB\right) = \sum_i Att\_factors_i = \alpha\left(\frac{dB}{km}\right) \cdot L(km) + \alpha_{conn}(dB) \tag{4.2}$$

Using equation 4.1 it is possible to estimate the optical power the PV cell is receiving (P_{out} (dBm)). In order to do so, it is required to know the optical emission power from the HPLD (P_{in} (dBm)) and to previously obtain its attenuation factor (Att (dB)). This factor, calculated with equation 4.2, is going to take into account the losses from the fiber (α (dB/km)), depending on the length of the fiber used (L), and the external attenuations caused by the connections at both ends of the fiber.

Once knowing the value for P_{out} (using W units), it must be multiplied by the efficiency of the device, so that it is possible to infer the electrical power that the described link will generate.

Chapter 5

SYSTEM DESCRIPTION

For the whole implementation of the instrumentation system, the project was divided in different stages, illustrated in fig.5.1. The separation of the processes will ease the development and assure all the components are working correctly before moving onto the next stage.

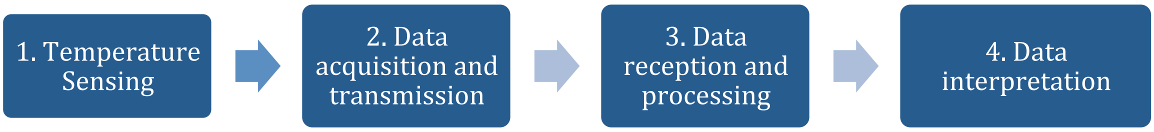

Figure 5.1. System stages

- The **temperature-sensing** block refers to the design of the optical sensor, including both the emitter and receiver driver circuits. The design procedure includes the theoretical analysis of the circuits, and the selection of the most appropriate devices composing it, including the parameters values (such as resistances). Once the models are analyzed and their responses measured theoretically, a second test trial is done using the virtual simulator Multisim that tests the circuit's response under ideal circumstances. This finalizes the theoretical analysis of the design, and is when the experimental development starts. This is done using the Electronica Department resources in the university, which allows building the circuits and measuring its output signals. In order to make sure the system model is working correctly, and meets all the requirements, the obtained experimental values are compared to the ones previously theoretically obtained. Once it is assured that each individual system is working as desired, the next step is the development of the fiber optic sensor. The coating will be pealed of and the fiber modified with a macrocurtvature design. After polishing the fiber each end is connected to one of the light emitter/receiver units, having a full sensor system.

- The communication design includes the following two blocks: **Data acquisition and transmission** and **Data reception and processing,** respectively. The selected data transmission is based on the ZigBee wireless communication protocol and will use the XBee modules for the adaptation to the sensor.
  The implemented sensor network will be composed of two nodes, one acting as a central node whereas the other will act as a remote sensing node, so it will use a point-to-point communication topology. The remote sensing node will be referred to as the emitter node. The central node will work as the receiver of the information data, and will be wired-connected to the computer, which will have an active control interface during the transmission. Each node will include as components: one Arduino One board, one XBee module and one XBee shield.

The objective of each node will be different:

- The emitter node, which corresponds to the **Data acquisition and transmission** block**,** will be connected to the optical sensor through the Arduino board. The microprocessor will obtain the values from the sensor, will convert them into a digital package and then transmit them to the XBee module, which will transmit the package to the established destiny address (the receiver).
- The receiver, which corresponds to **Data reception and processing** block, will receive the data package from the emitter and will transmit it to the computer through the serial communication of the USB port.

All the components of the communication require their own software configuration. The Arduino microprocessor will have to be programmed in the emitter node. And both XBee modules need to have their commands set up, including: origin and destination addresses, the channel settings, the identification and the type of devices they are (the role they play on the network).

- The **data interpretation** block analyzes the data obtained from the sensing scheme. A user interface will be created for the manipulation of the data using the LabView virtual instrumentation software. LabView is able to control the Arduino board connected to the computer though the USB serial communication, and to obtain the required data from it. As the sensor values are captured by the program the LabView sequential functions will “read” that data and give the equivalent temperature for the value. This function has to be previously designed and implemented from a previously and experimentally obtained calibration curve, studying how the temperature alterations affect the sensor.

An extra implementation for the project will be the use of power over fiber (PoF) as a power source. This new method will be tested on a full operative system, and the results studied to see its capacity and the possibility of a future installment on instrumentation sensors.

A flow chart of the full system operation is shown on the diagram on the next page, figure 5.2.

Figure 5.2. System flow diagram

For a better understanding of the different stages illustrated in Fig 5.1 each block will be described independently and in detail in the following chapters.

Chapter 6: Sensor Design	→	Temperature sensing.
Chapter 7: Communication design	→	Data acquisition and transmission & Data reception and processing.
Chapter 8: Computer interface	→	Data interpretation.

5.1 SYSTEM COMPONENTS

The following list includes all the hardware devices composing the system:

- 1 optical fiber sensor
- 1 optical source: LED IF-E96
- 1 optical receiver: photodiode IF-D91
- 3 operational amplifiers TL081
- 1 transistor Q2N2222
- Specific resistor parameters
- 2 Arduino One boards
- 2 XBee modules
- 2 XBee shields
- 1 USB cable
- 1 computer

But the system will not only require the manipulation of the hardware of the devices. The configuration of the software of some of the components will also be necessary. These programs are:

- *Multisim*: for the virtual analysis of the sensor circuits
- *Arduino Developer*: for the programming of the microprocessor on the Arduino board.
- *XCTU software*: for the configuration of the commands on the XBee modules
- *LabView*: program used to generate the interface for the user, and the manipulation of the sensor data to obtain the temperature.

The annex includes the steps followed for the development of the software and the Arduino code used.

Chapter 6

SENSOR DESIGN

A sensor is a device capable of detecting actions or any kind of external perturbations, and responds to them consequently.

Sensors are gadgets that allow obtaining information about the environment and interact with it. They work like the human sensorial system, but for machines and robots.

This project requires the design of a sensor capable of measuring the temperature. These types of sensor measure changes taking place on the current signal of the circuits, based on the temperature variation affecting the sensor head, this means the temperature the sensor is submitted to.

The selected sensor for this project operates in the optical domain and employs a plastic optical fiber to perform a macro-bend optical intensity sensor. It encodes the temperature information into an optical magnitude, and particularly into optical power, i.e. light intensity, variation. Its principle of operation was described in a former section.

A scheme of the fiber sensor design is represented in Fig. 6.1. The emitter and receiver are connected via a plastic optical fiber in which a macro-bend has been done thus obtaining light intensity variations as temperature changes. Finally, the electrical magnitude obtained at the receiver circuit is directly related to the temperature variations affecting the optical sensor.

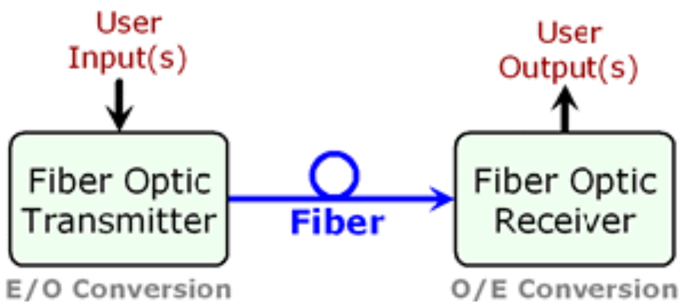

Figure 6.1. Fiber Sensor design [53]

This chapter provides a full description of the sensor design as well as its performance.

The circuit design is a key point in the final resolution; the sensor requires the highest precision possible for an accurate analysis of the temperature, hence better results, and a higher control and monitoring of the environment. The chosen circuits optimized the signal and reduce or eliminate all the possible interferences.

The best tool for the circuit design is the National Instruments program Multisim. It allows virtually designing the circuit with its specific parameters and obtaining the response the circuit would experimentally give under ideal circumstances.

These previous procedures set a foundation of the expected results from the experimental development. The principal aim of the theoretical analysis is the selection of the most suitable design for the experimental circuits. Once implemented the system, the output signals will be measured and compared to the theoretical results, to make sure is working correctly.

6.1 EMITTER

The emitter application on the sensor systems is based on the modification of the original magnitude entering the circuit into the sensor´s transmission magnitude. For the particular case of this project the analogical components work with electrical energy, which will be transformed into optical energy by means of a LED. This device will be connected to fiber optic in which the light will propagate through.

The design of the circuit consists on the selection of the parameters and their adaptation to the signal. As an optical source an IF-E93 LED is employed based at a forward current of 20mA, as the vendor suggests [54].

The LED functioning consists on the emission of light based on the entering electrical current. These two parameters have a proportional relationship, so the greater the current going through the LED the greater optical signal emitted. In order to measure the luminous magnitudes the wavelength (λ) parameter of the visual spectrum is used.

The selected LED includes a datasheet, where the manufacturer indicates the typical values for an active LED. Using the wavelength and current parameters values from this datasheet it is possible to relate them to the actual current and wavelength on the circuit. This relationship is established in equation 6.1, where the 522nm stands for the typical wavelength of the LED and the 20mA is the current at that wavelength, as indicated on its datasheet. The unknown λ is the value of my circuit's wavelength, and the I_C stands for the current the LED is working on to obtain that λ.

$$\lambda[\text{nm}] = \frac{I_C \cdot \lambda_{datasheet}}{\text{I}_{datasheet}} = \frac{I_C[mA] \cdot 522}{20 \cdot 10^{-3}} \quad (6.1)$$

Because the LED in this project has to be specifically attached to the fiber, all the studied options included an adapter to this type of sensors, as a plug-and-play connector. The selection of the LED was based on a power balance analysis of two options, the red and green LEDs from the same company. They both have different spectrums, which gives different results. This analysis will be previously explain on this chapter, but the final design includes the green

LED IF-E93, being the most suitable option because it gives the most optimized system.

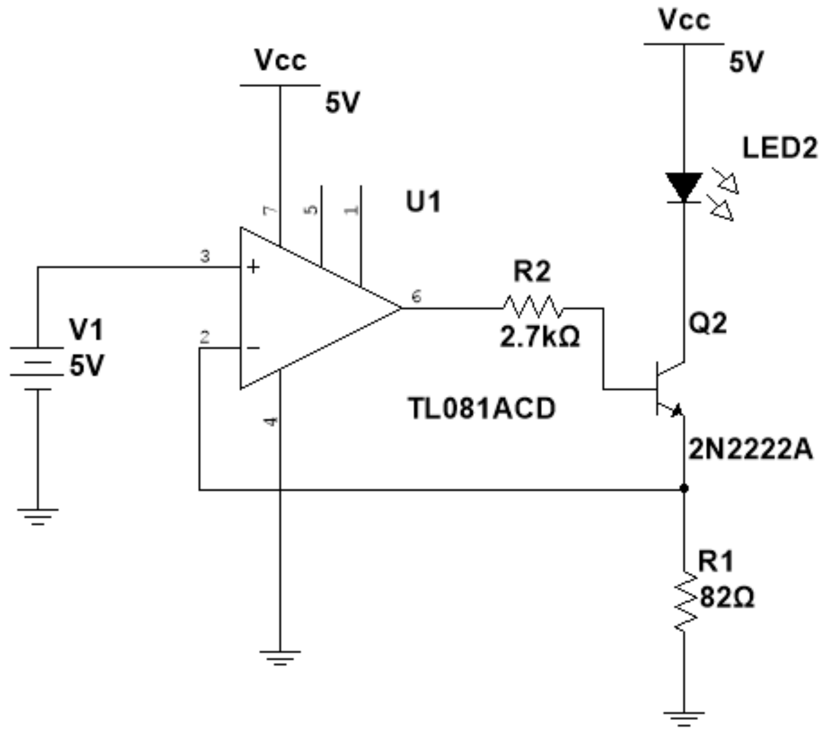

Figure 6.2. Emitter circuit design

The figure 6.2 shows the full schematic of the emitter driver circuit, including the parameters and its selected values, that implements a constant current electronic scheme.

The circuit is powered using +5V, it was adapted to this value because when adding the communication components from the Arduino One board it needs that same power, and using one source for the full system facilitates the understanding, gives a cleaner design and reduces the interferences risks.

The values of the parameters were set to fit the characteristics of the rest of the components. The circuit is a basic design of instrumentation emission that perfectly works for the desired sensor and adapted to the requirements of the project. The components types (transistor and amplifier) were selected from the available options in the lab, and the resistances values according to circuit requirements.

6.1.1 Led Selection

One of the main elements of the sensor is the optical source, which is responsible of converting the electrical signal into an optical one for its later transmission.

When selecting the most suitable LED for the sensor, different characteristics had to be taken into account, analyzing primarily the optical fiber characteristics as well as its attenuation coefficient, i.e. power losses, depending on the material from which the fiber is made.
The attenuation is expressed as Eq. 6.2 and defines the power loss during its propagation throughout the optical fiber:

$$Att = \alpha[dB] = -10 \cdot log \frac{P_{out}[W]}{P_{in}[W]} \tag{6.2}$$

Where Pout and Pin stand for the power output and power input, respectively. Considering an optical fiber distance unit, the attenuation coefficient of an optical fiber can be given in terms of dB/km (or dB/m alternatively). Just checking the optical fiber attenuation spectrum one could select a proper operating wavelength to transmit light via an optical fiber, and so with the optical source

In order to select the best LED option for this sensor system, an analytical comparison between two LEDs was done: the green LED IF-E93 and the red LED IF-E96 [55]. Both devices are from the same company, with a connector adapted to the optical fiber, but each work with different wavelengths.

	λ [nm]	P_{Led} [µW]	I [mA]
Green Led [*IF-E93*]	522	465	20
Red Led [*IF-E96E*]	645	325	20

Table 6.1. IF E93 [54] and IF E96E [55] parameters

In the previous table 6.1, we can observe the values of the wavelength and its current equivalent, as well as the output power depending on the input power of each of the LEDs. These are the used parameters to theoretically calculate the power traveling through the fiber, and the outputting quantity at the opposite end of it.

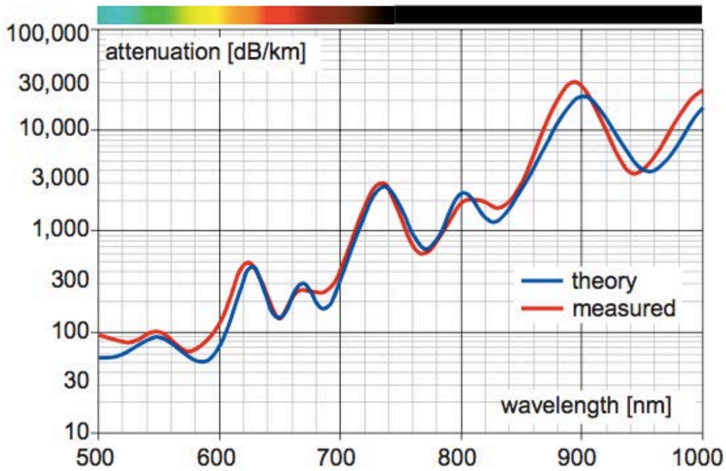

Figure 6.3. Attenuation spectrum of the PMMA-POF [28]

The figure 6.3 shows the graph from where we can obtain the attenuation of the plastic fiber used in the sensor. In order to do so, we must know the wavelength of the working Led.

	λ [nm]	Att [dB/km]
Green Led [*IF E93*]	522	100
Red Led [*IF E96E*]	645	135

Table 6.2. IF E93 [54] and IF E96 [55] parameters

As we can observe in the previous table 6.2, the values of attenuation show that the difference between the LED used reaches 35dB; this difference in 1 km of fiber between two λ means a power ratio of $10^{35/10}$=3162,27. Which means that the input signal is attenuated around the factor of 3162,27 per km depending on the wavelength used.

When the power going through the fiber reaches the photodiode in the receiver circuit, the device takes the optical signal and converts it into an electrical magnitude. This conversion is based on the relationship between the input power and the output current of the photodiode, later explained on this chapter.

When analyzing this final part, the theoretical calculation of the output power was necessary. With it and taking into account the responsivity of the photodiode according to the wavelength used, the expected photocurrent generated can be computed.

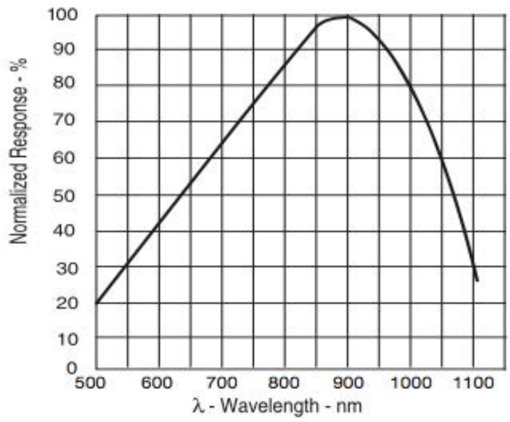

Figure 6.4. IF D91 response versus wavelength [56]

The figure 6.4 shows the graph from the datasheet that represents the responsivity of the *IF-D91* photodiode [56] according to the entering wavelength.

	Rmax [μA/μW]@900nm	Response [%]
Green Led [*IF E93*]	0,5	23
Red Led [*IF E96E*]	0,5	52

Table 6.3. IF E93 [54] and IF E96E [56] parameters

When comparing the values from table 6.3 it is remarkable that the photodiode has a greater response, i.e. sensitivity to the red LED, which will make it the most suitable option. However the power losses difference can be negligible when compared to the attenuation difference of 35 dB between the two LEDs. This parameter is a lot greater for the red LED, which makes the green emission the more, optimized of the two. The quantity of emitted light going through the fiber has lower losses, which means the photodiode will receive more power when using the green LED.

.

LED			LED		
If	2,00E-02	A	If	2,00E-02	A
Pled	4,65E-04	W	Pled	3,25E-04	W
Perdidas por inserción LED			**Perdidas por inserción LED**		
α	0,9	dB	α	0,9	dB
Pin	3,78E-04	W	Pin	2,64E-04	W
FIBRA			**FIBRA**		
Att	10	dB	Att	13,5	dB
Pf	3,77966E-05	W	Pf	1,18E-05	W
Perdidas por inserción FOTODIODO			**Perdidas por inserción FOTODIODO**		
λ	0,99	dB	λ	0,99	dB
Ppd	3,00921E-05	W	Ppd	9,3947E-06	W

Figure 6.5. Green and red LED power balance. A 100m-long plastic optical fiber patch cord is assumed.

This figure 6.5 shows the final theoretical results of the whole emitter-receiver set, using the ideal values from each datasheet and the attenuation values mentioned before. The tittle colors refer to the LEDs color.

Figure 6.6. Picture of the LED IF- E93 [54]

The figure 6.6 is an image of the appearance of the selected LED, IF-E93. It can be observed an external holder that permits inserting the fiber and attaching it securely, holding in it there and assuring the wire is well placed and covering it with the rest of the component, so the transmission between the two can be as efficient as possible.

6.1.2 Theoretical Results – circuit analysis

This theoretical analysis is divided in 3 stages.

The V_{CC} value corresponds to the DC power supply, which was set to 5V to uniform the Arduino board power supply. This value also enhances the results when testing the power supply through power over fiber (PoF) technique.

The circuit also uses an amplifier TL081 that allows increasing the output signal based on its inputs.

The transistor 2N2222 [57] works as a switch for the current that goes through the LED.

In order to generate a current, the transistor has to work in its active region, which means the value of $V_{CEact} > V_{CEsat}$, where the value of V_{CEsat} can be obtained from the datasheet of the transistor, and the current has to be greater than 0, see Fig 6.7 shows the schematic distribution of the transistor.

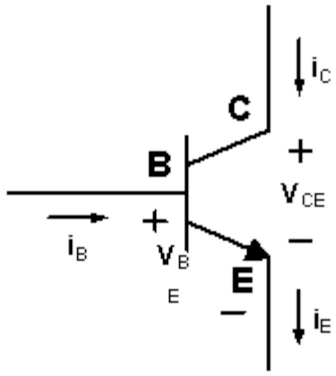

Figure 6.7. BJT transistor current schematic distribution

When working theoretically, the values used are obtained from the datasheet of the specific component and it is assumed that it works under ideal circumstances. The values from the datasheets are:

Transistor 2N2222

V_{CE} = 0,3 V (=V_{CEsat})
V_{BEon} = 0,7 V

LED IF-E93

V_F= 3,1 V
I_{LED}= 20 mA

I_{LED} is the chosen current for the analysis. For the selection of the value two requirements are taken into account: it has to guarantee an active LED, so a polarization current suitable for the LED and the transistor has to be working in its active state. The power emission in this analysis is not calculated, because assuming that the LED works with the manufacturer current it means it also works with the manufacturer optical power, both values obtained from the datasheet.

The equation 6.3 obtained from the basic theory of an operative transistor makes it possible to calculate the relationship between the two currents outputting the transistor, I_C and I_E, and determine that their value is almost identical, it will be assumed as the same value for the rest of the analysis. This will also determine that the transistor is assumed to be working on its active state.

$$I_C = I_E \cdot \frac{\beta}{\beta + 1} \cong I_E \quad (6.3)$$

The value of the constant β = 200 is obtained from the datasheet. As it can be observed, the number is so big that when adding it to 1, the difference between them makes it negligible.

Once known and checked that both currents have the same value, the applied term for both during the analysis will be: I_{LED}.

$$I_{LED} = I_C = I_E = 20\ mA$$

This sets all the theoretical values known. The following step is to take the different stages of the circuit, and using the electrical theories for each component obtain their respective equations and analyze the results for the design developing.

In the first stage it was applied the Kirchhoff laws and the equations for a BJT transistor, obtaining the next results:

$$V_{cc} = R_1 \cdot I_E \qquad (6.4)$$

$$V_{CC} = V_F + V_{CE} + I_E \cdot R_1 \qquad (6.5)$$

$$V_{CE} = V_{CC} - V_F - I_E \cdot R_1 > V_{CEsat} \qquad (6.6)$$

From the equation 6.4 and 6.6 we determined a threshold of the R_1, limiting the values that will work maintaining the transistor in the active state.

$$80\ \Omega < R_1 < 250\ \Omega$$

The 80 Ω and 250 Ω values were the result of the equation 6.4 and 6.6 respectively. The equation 6.6 comes from the clearing of 6.5, because the desired value was V_{CE}, in order to apply the theory transistor requirement of $V_{CE} > V_{CEsat}$, to maintain the active state in the component.

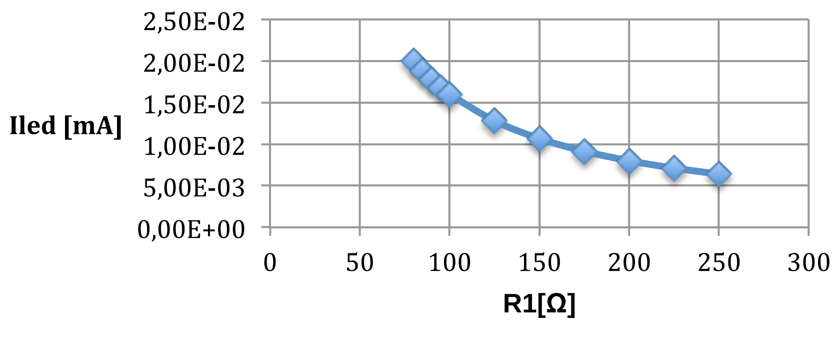

Figure 6.8. I_{LED} versus R_1

The figure 6.8 shows how the variation of the resistance R_1 affects the current I_{LED}. It was based on the main transistor equation 6.5. The graph states how when increasing the resistance, the current decreases. This relationship is based on the Ohm Law 6.7, where both values are inversely proportional to one another

$$V\ [V] = I[A] \cdot R[\Omega] \qquad (6.7)$$

From figure 6.8 it is possible to determine that the best value for the system is the smallest possible, 80 Ω. It assures that the circuit current for the LED is 20mA, and a working transistor stable in its active state.

The experimental resistances have standard values that mean there is no 80Ω resistance available. It had to be greater than 80 Ω, and the closer existing value is 82 Ω, so it was determined that: **R_1= 82 Ω**.

The value of R_2 was determined from the equation 6.8 and 6.9, both from the theoretical performance analysis of the transistor.

$$I_C = \beta \cdot I_B \tag{6.8}$$

$$I_B \cdot R_2 = V_{BE} + I_E \cdot R_1 \tag{6.9}$$

Knowing that β= 200, from the 2N2222 datasheet, and using the R_1 previously determined (82 Ω), the equations determine that the value for $I_B = 0{,}1$ mA, and so the definitive value of: **R_2 =2,7 kΩ**.

6.1.3 Experimental results

Before experimenting directly on the lab, the circuit was simulated and tested with the Multisim platform. It allows simulating the system and observing the reaction and results of it. The computer works with ideal circumstances, but gives an orientation to the following lab implementation. The results from both situations should be similar, assuming an error in the lab materials or components in the opposite case, forcing a different approach.

This program allows to measure using a simulated ammeter that permits selecting the specific area that is going to be measured. This will be a simulation of the following measurement on the lab.
The figure 6.9 shows an image of the emitter circuit developed in the lab.

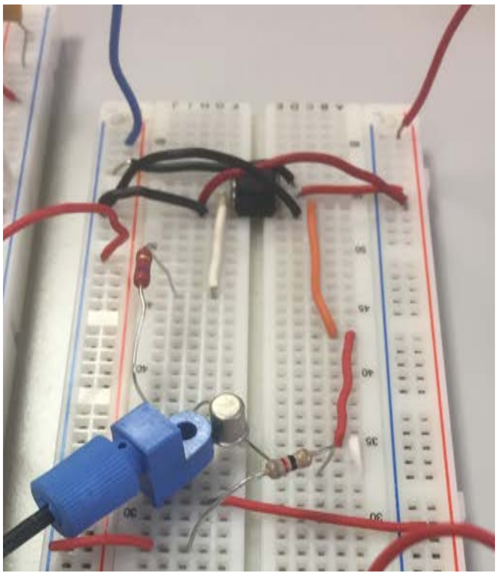

Figure 6.9. Emitter driver circuit

The measurements obtained from the experimental circuit were compared with both the theoretical and the simulation results to make sure the emitter driver was working as expected, and the performance was correct.

Experimental Values			
I_C	19,18 mA	**V_F**	3,4 V
I_E	19,4 mA	**V_{CE}**	0,06 V
I_B	0,66 mA = 660 μA	**V_{BE}**	0,7 V

Table 6.4. Experimental emitter values

Simulated Values			
I_C	16,958 mA	**V_F**	3,4 V
I_E	17,1 mA	**V_{CE}**	162,02 mV
I_B	145,03 μA	**V_{BE}**	705,84 mV

Table 6.5. Simulated emitter values

Theoretical Values			
I_C	20 mA	**V_F**	3,1 V
I_E	20 mA	**V_{CE}**	0,26 V
I_B	100 μA	**V_{BE}**	0,7 V

Table 6.6. Theoretical emitter values

Even though the lab conditions are not ideal, the results were, as predicted, all very similar to ones obtained in the other two cases, which can be referred to as the ideal values. The variation of the parameters could be due to the not exact values of the resistances, which have a tolerance that can vary the result. When experimentally measuring the used resistances the values obtained with the ohmmeter were R_1= 82,5 Ω and R_2= 2,72 kΩ, respectively, proving the not ideal conditions.

It can be appreciated that there is a small variation in some of the results, which could be due to different anomalies. When comparing the values of I_B, the experimental result appears to be considerably lower than the theoretical calculations; this may be due to value of β applied, which is different to the assumed value of 200 (in the theoretical analysis).
Even so the circuit works properly, the LED was immediately emitting a green light when connecting it to the power source.

6.2 SENSOR

This project uses an intensity-based optical sensor based on the radiation loss variation due to temperature changes around its sensitive area. The latter is obtained just performing a macro-bend to a bare plastic optical fiber to increase the sensitivity of radiated light with regards to temperature.

The sensor works measuring the attenuation of the spectral transmission of the light going through the sensor. It can also work taking measurements from the variation of the radiation factor induced from external lighting, which using a different beam light known as reference is possible to determine the magnitude in the external effect.

This project uses a plastic optical fiber as the optical sensor itself. Temperature phase sensors are based on phase changes of an electromagnetic wave traveling along an optical fiber caused by temperature changes. The designed sensor consists on a low-cost intensity macro-bend temperature sensor based on polymer optical fiber. These types of sensor are less fragile and easier to handle than the silica optical fiber.

This is an intensity sensor that uses a macro-bend design, where the losses induced by the bending effect depend on the numerical aperture that changes with the temperature. As well as the refractive index of the core and cladding, which also depend on the temperature [37].

The fiber basically consists of two concentric cylinders, namely core and cladding both with their specific refraction indexes. The following image 6.10 shows the appearance of a fiber wire, with its three components. Number 1 refers to the core, number 2 the cladding and number 3 the coating. The coating covers the core and cladding. It provides mechanical strength and it is only useful for protection purposes against external risks or degradation factors, mainly humidity.

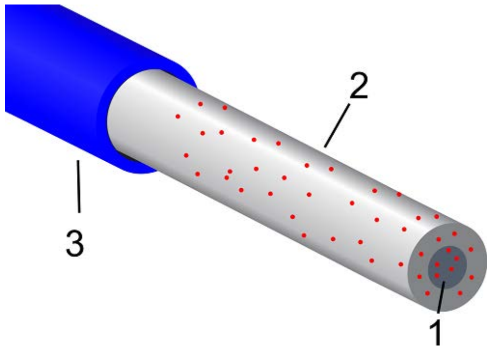

Figure 6.10. Fiber layers distribution

As a fiber it has two ends, one will be connected to the light emitter (LED) whereas the other will be connected to the receiver (photodiode).

The reasons for the selection of plastic optical fiber sensors were established in the previous *Chapter 2 Temperature Sensors*. In order to reassure this choice, the following points are the main characteristics of the fiber that make it the best option:

- No electromagnetic interferences.
- Cheap, light and flexible.
- Low losses based on the wavelength.
- Great compatibility and sensitivity.

One of the main parameters that affect the attenuation characteristics of a fiber is the material from which it is made This is why the only way to obtain a theoretical approximation of the values the fiber is working with, is by estimating the power losses with an arbitrary number for the attenuation.

For the theoretical power input/ output analysis of the fiber the equation 6.10 was used. In order to do so, it was assumed attenuation on the fiber of 10 $^{dB}/_{m}$, and for the power inputting the fiber the value theoretically calculated was used. This gives an approximation of what the power existing the fiber will be at the photodiode end of the transmission.

$$P_{out} = 10^{\frac{10}{10}+\log(P_{in})} = 30\mu W \tag{6.10}$$

An experimental method to observe the fiber is working correctly, hence it is transmitting, once the system is powered up, the output signal should vary when moving the fiber. This means that the changes affect the sensor.

The plastic fiber has a wire structure. The temperature variations affect the fiber modifying the optical magnitude. The relationship between the resulting value and the temperature on the fiber is calculated with a calibration curve, included in the computer interface explained in the following *Chapter 8*

Computer Interface. For a better exposure of the sensor a bare fiber is employed, i.e. a fiber in which the coating is stripped off. Moreover, the stripped region is also curved at its ending points thus increasing the sensor's sensitivity to temperature variations.

This fiber bent causes the higher order light rays to escape the core, and therefore causes losses. The insertion losses of the sensor at a specific temperature increase as the bend radius decreases. [37].

When working on the lab, the initial results were obtained with a room temperature of 25ºC. The equation 6.11 reflects how the temperature alters the beam of light on the core of the fiber exposed. The modification is reflected on the refraction index of the cladding. n_0 Is the reference value of this magnitude and $n_{cladding}$ gives the resulting index after the alteration. The temperatures involve are T and T_0, which indicate the new temperature sensed by the fiber and the reference temperature, which is T_0 =25º, respectively. The relationship between these two parameters is equivalent, so the numerical aperture increases when the applied temperature increases. This increment happens because an optical ray is unguided at the reference temperature becomes guided at temperatures greater than the reference temperature [37].

$$n_{cladding} = n_0 + \alpha_n \cdot (T - T_0) \qquad (6.11)$$

The local numerical aperture increases as the bend radius increases up to the local numerical aperture for a straight fiber. The α_n is the thermal-optical coefficient, based on the material used in the cladding. For the polymer fiber employed within this work this value is $-5 \cdot 10^{-4}\ [1/{}^{\circ}C]$ [15].

The temperature variation is experimentally measured using a hot plate as heat source see Figure 6.11. The machine used was LTS35 that measures the temperature in liquid crystal as a heat source, and causes an increase in the temperature as a consequence of the temperature variations induced by the control unit TP94, allowing to obtain different result measurements depending on the produced temperature variations.

Figure 6.11. Fiber sensor on hot plate

6.3 RECEIVER

The sensor system is composed of two circuits in order to adapt the signal. The receiver circuit is composed of the devices that transform any given magnitude into electrical ones.

The main component of the receiver circuit is the photodiode, which converts the optical input signal into an electrical signal, creating the current that will travel through the circuit. The used photodiode is IF- D91, which was selected because of its adaptation to the optical fiber.

The photodiodes are use in a great variety of applications to transform light into electrical current. For applications that require high velocity and an elevated dynamic scope are often used amplifier transimpedances circuits that include photodiode devices. The figure 6.12 shows the design of this project receiver circuit for the sensor, which is a trans-impedance circuit, with its amplifier, a resistor and a photodiode.

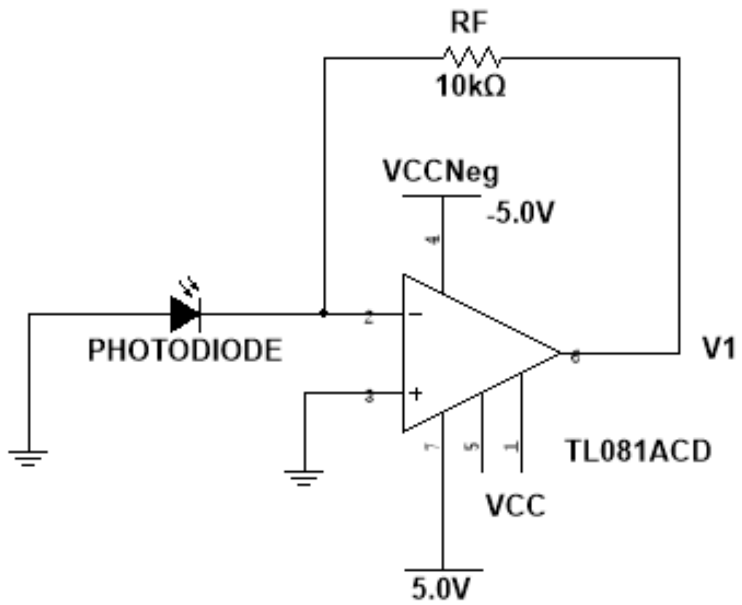

Figure 6.12. Receiver circuit design

The circuit has the photodiode in a photo-conductor mode, with a polarization voltage applied to the cathode. The virtual connections between the two inputs of the operational amplifier maintain the anode connected to ground, applying a constant inverse polarization voltage through the photodiode. The greater the polarization tension is in the diode, the lower the capacity of the photodiode has to be. When designing the circuit it is important to take into account the power of the optical signal injected in the photodiode. The value theoretically obtained was around $\mu W = 10^{-6}$, which complicates the following stages of the data acquisition and previous analysis, because of its small size. The input optical power is converted into electrical current, following the behavior given by Eq. 6.12,

$$I_{Pd} = \mathcal{R} \cdot P_{in} \tag{6.12}$$

The $\mathcal{R}$ of the equation responds to the responsivity of the photodiode, which depends on the wavelength (λ) of the chosen LED and the photodiode characteristics. In the case of this project, IF-E93 has:

$$\lambda = 522nm$$

Observing the curve of the photodiode response, see fig. 6.4, when working with a light wavelength of 522nm, there is a 23% normalized response on the photodiode. Knowing that the normal responsivity of IF-D91 is 0,4 $^{\mu A}/_{\mu W}$ the final responsivity for IF-D91 of the designed system is:
$\boldsymbol{\mathcal{R}} = 0{,}23 \cdot 0{,}4 = \mathbf{0,092} \left[{}^{\boldsymbol{\mu A}}/_{\boldsymbol{\mu W}}\right]$.
The low $\mathcal{R}$ confirms the weak intensity signal coming out from the photodiode, so the value of the signal must be increased in the following steps, using an adaptation circuit that amplifies the signal, which is why the selected design is: an operational amplifier.

The current from the photodiode, I_{PD}, is amplified through the transimpedance amplifier and it is converted in an output voltage with the gain resistance, R_F, of trans-impedance. However the result is not going to be the exact result of that gain, because the amplifier "takes" part of that current coming in as the polarization current, which ends up decreasing the output voltage value.

The greater the gain resistance is, the greater effect it has. It is important to pick an amplifier with a polarization current low enough to acquire the dynamic scope and total precision required. This dynamic scope is the relationship between the maximum input signal and the noise, which makes it important to select an operation amplifier with low enough noise. They are as important the current noise, and the voltage noise of the amplifier. The current noise is multiplied by the resistance, triggering the appearance of noise as a mistake of the output voltage. The amplifier voltage noise multiplies by the noise gain, so that for greater values of R_F the current noise becomes more dominant.

The gain of the transistor is determined by the resistance, as shown in the following equation 6.13, where V_O is the value of the output voltage after the signal goes through the amplifier.

$$V_O = -R_F \cdot I_{Pd} \tag{6.13}$$

It is assumed that the light that comes out of the LED from the emitter circuit is going to have losses once traveling through the fiber, and even more losses when entering the photodiode, caused by the possible errors in the adaption of the cable to the device. Because the exact values of the losses are unknown until starting with the experimental calculations, the next step was the selection of the resistor R_F value. In order to select it the circuit was fully implemented in the lab, and the resistance was modified until finding the most fitted option.

Assuming losses of $\lambda = 10dB$, due to the attachment of the fiber to the photodiode, and with the experimental results previously obtained from the emitter circuit we can theoretically estimate the power coming into the photodiode from the fiber.

$I_{LED} = 16{,}95mA$
$P_{LED} = 58{,}26\, mW$

$$P_{in}\ [W] = 10^{logP_{out} - \alpha/10} = \ 25{,}5\ \mu W \qquad (6.14)$$

In equation 6.14 the P_{in} stands for the power entering the photodiode, using the 10 dB losses and the P_{out} indicates the power travelling through the fiber coming from the LED.

With this value as the incident power, using the equation 6.12 and the responsivity of the photodiode, the current is:

$$I_{PD} = 25{,}5 \cdot 0{,}4 \cdot 0{,}23 = 2{,}24\ \mu A \qquad (6.15)$$

The entrance capacity of the photodiode also limits the bandwidth. This means the input condenser impedance can be considered as the gain resistance (R_G). Because the bandwidth is inversely proportional to the gain based on the constant nature of the amplifier, a high entrance capacity means a limited bandwidth for the circuit. It is important to select an amplifier with low entrance capacity and to design a schematic of the circuit that helps decrease it. The chosen amplifier is TL081, which adapts to these requirements and to the emitter design of 5V as powering source, easing the later powering of the Arduino One board.

With the theoretically calculated photodiode current (I_{PD}), it is possible to estimate the value of the gain resistance (R_F) using the equation 6.13. For the output signal value (V_O) 5V were used. This assumption is based on the adaptation of the sensor to the communication technology. This procedure includes an Arduino plate, which can only read 5V from its analogical pins. Giving it the greater available value will guarantee high results, which increase the chances of a correct "reading" of the output signal, and a more efficient transmission and analysis. The theoretical value for 5V is then R_F= 2,23MΩ.

If we use a high value resistor for R_F like 2,23MΩ, the output signal will most likely be saturated, due to the impossibility of the amplifier to supply more voltage than is getting, and will no longer be amplifying the signal. Also, with a value as high as that one, the system will have a great amount of noise, like previously explained in this chapter.

The next step was to manually change the resistor values and measure its response on the experimental circuit. The results can be observed in the following table:

R_F	I_{PD}	V_0
510 **Ω**	11,1 µA	- 8 mV
1 **kΩ**	14,5 µA	-14,5 mV
10 **kΩ**	15,7 µA	-149 mV
1,5 **MΩ**	0,31 µA	- 0,8V
4,3 **MΩ**	0,272 µA	-1,17 V
6,8 **MΩ**	0,186 µA	-1,86 V

Table 6.7. Receiver response results

When selecting the value for the resistance it is important to study the output results [V_0]. Observing table 6.7 it is determined that a second stage that will amplify and invert the signal value will be necessary, because it is recommended to use values between 3-5 V as the output results, for the data acquisition and analysis procedures.

The resistances with greater magnitudes are highly un-recommended, because they have a higher chance of generating noise and decreasing the bandwidth of the circuit, This means that the three last values from table 6.7 are discarded, because they are all in the MΩ magnitudes.

The final chosen resistance was **R_F = 10 kΩ**. Picking one of the bigger resistances will increase the noise and disturbances of the circuit, so it is not recommended. And even though the signal is going to be amplified again, the highest the output voltage value is, the less noise the second stage will generate, because it will require smaller impedances and an easier system. Looking at both stages of the receiver circuit as a full operative system, 10 kΩ is the most suitable option for R_F.

6.3.1 Inverter Amplifier

The inverter amplifier refers to a basic circuit design type. This implementation is named this way because the output signal is the inverse of the entrance one in polarity, although it can be greater, the same or smaller, depending on the gain attributed to the amplifier en closed loop. The signal is applied to the inverter terminal, or negative amplifier and the positive or non-inverter is connected to ground. The R_4, which goes from the output terminal to the negative input, is called feedback.

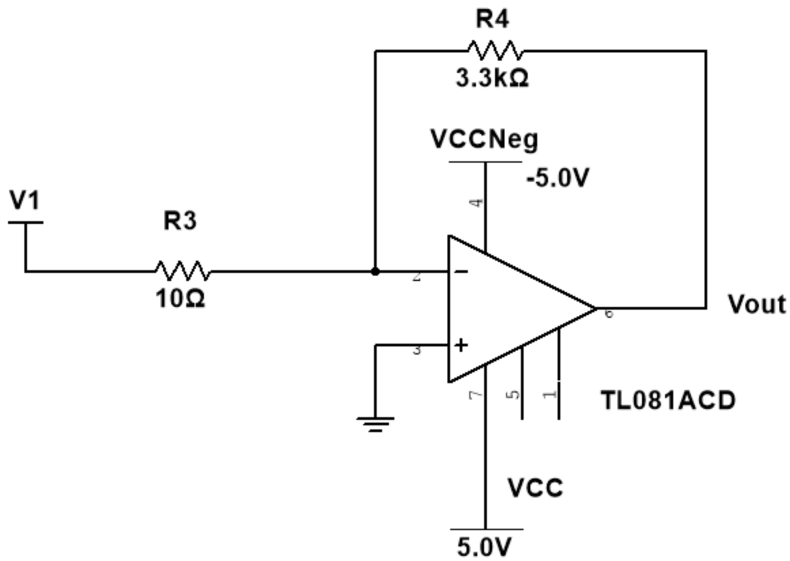

Figure 6.13. Inverter Amplifier design

The design is a close loop circuit, so the determination of the gain will be done using a virtual short-circuit, with negative feedback. The input currents of the amplifier are assumed to be null, and the positive input potential is the same as the negative input. This means that the current circulation through R_3 will have to continue its way through R_4 until the output terminal.

The value represented as V_1 on fig. 6.13, is the output signal voltage of the receiver circuit, which is around the mV order with a negative sign. As previously explained, the value has to be amplified and inverted for the following stages of the project, where it will be working with an Arduino plate which can only read analogical values from 0 to 5V. The desired signal result is around 3-5 V to assure a correct reading from the Arduino and a precise and efficient analysis of the temperature.

This Arduino plate, which contains a microprocessor previously programmed, will acquire the analogical data and transform it into a digital package ready to be sent between the antennas (one connected to the sensor and the one connected to the computer). The communication design will be explained on the following *Chapter 7 Communication Design*.

The inverter amplifier design corresponds to fig. 6.13, where the two resistances work as the gain of the amplifier (V_{out}/V_1). This gain is calculated applying Kirchhoff's Laws for the circuit analysis, and taking into the account the design assumptions ($V_+= V_-$ and $I_+= I_-=0$). The resulted equation is:

$$V_{out} = -\frac{R_4}{R_3} \cdot V_1 \quad (6.16)$$

The gain equation 6.16 shows how the variation of the output signal depends on the effect of the resistances on the input voltage. This means that when using a R_4 considerably greater than R_3 the output increases. The inversion is done with the negative sign, which comes from the negative feedback on the design.

Because the goal of this circuit is the increase of the V_{OUT}, R_4 has to be greater than R3. For an easier analysis R_3 was set to 10 Ω, and R_4 was tested with different and greater values to determine the most suitable one for the transistor gain.

The variation of the R_4 values was done manually on the lab. This means the resistor R_4 was replaced each time, and the V_{OUT} value measured to study its response. The following table shows the obtained results:

R_3	R_4	V_0	Gain
10 **Ω**	120 Ω	125 mV	12 $[V/V]$
10 **Ω**	1,2 kΩ	1,2 V	120 $[V/V]$
10 **Ω**	1,8 kΩ	1,88 V	180 $[V/V]$
10 **Ω**	3,3 kΩ	3,44 V	330 $[V/V]$
10 **Ω**	3,9 kΩ	Saturated	390 $[V/V]$
10 **Ω**	4,7 kΩ	Saturated	470 $[V/V]$

Table 6.8. Inverter amplifier response values

As table 6.8 shows the value of R_3 was set to 10 Ω, for simplicity reasons and the one varied was R_4. The last two options are automatically discarded, because the amplifier is unable to handle them, ending up in a saturation state.

For the selection of the resistance it is important to observe the V_0 values. Because the desired value has to be between 3-5 V, the selected resistance will be **R_4= 3,3 kΩ**. It gives the highest response possible. The gain of 330 $[V/V]$ does not generate an alarming amount of noise, and the acquired value reaches a suitable value for the following stages.

The following figure 6.14 shows the full receiver system, with both stages.

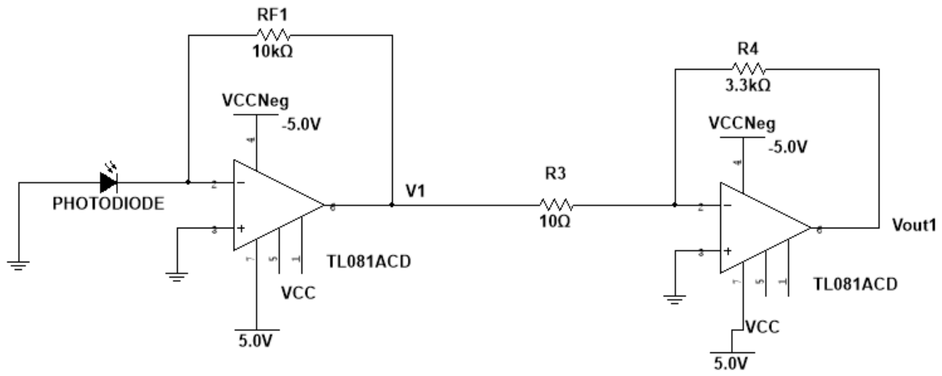

Figure 6.14. Receiver and inverter amplifier design. Full reception circuit

The following two figures 6.15 and 6.16 are images of the whole sensor design: with the emission, fiber and reception stages.

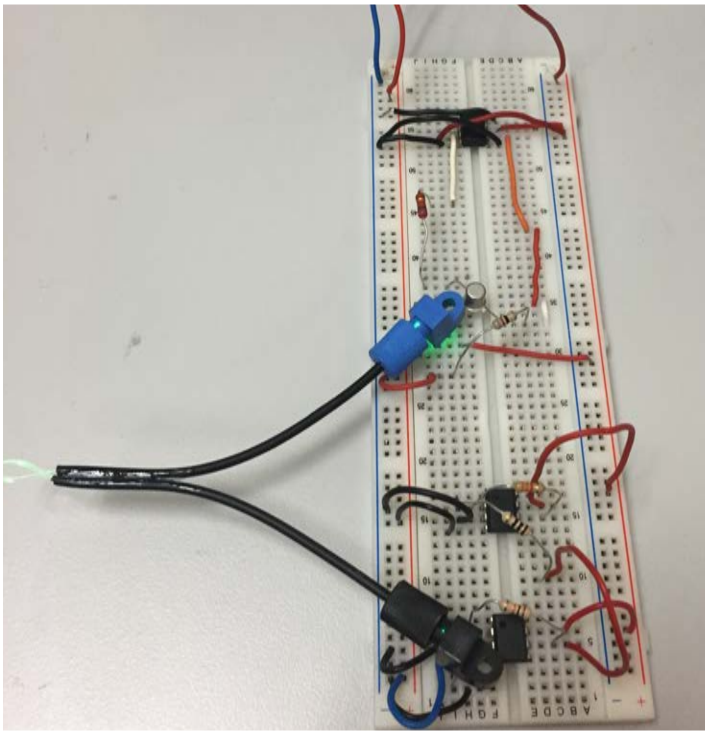

Figure 6.15. Full experimental sensor system

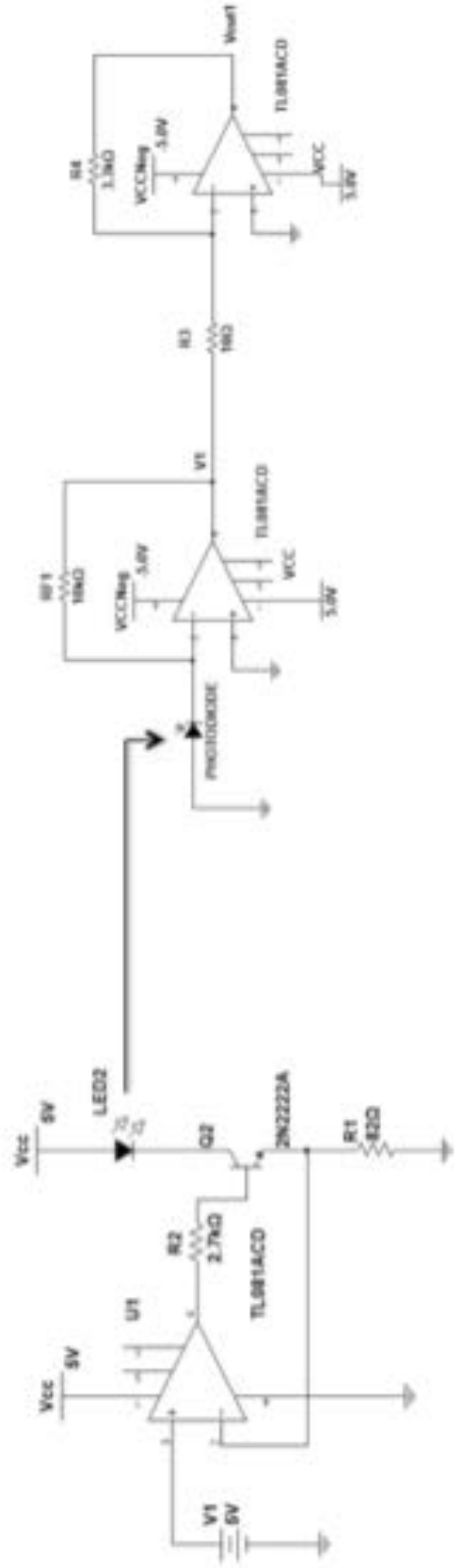

Figure 6.16. Full Sensor System design

Chapter 7
COMMUNICATION DESIGN

The communication is a process where one point transmits and another one receives information. It is required the existence of an emitter, a transmission medium performing a communication channel, and a receiver. The transmission method for this project will be through wireless protocols, using antennas that will work as emitters and receivers.

The wireless communication uses electromagnetic radiofrequency waves and a specific bandwidth between the devices. The greater effectiveness and reach between the systems is achieved when no obstacles are found between the antennas. The tendency to movement and ubiquity make more used wireless systems.

The aim of the project is to remotely monitor and control the designed temperature sensor. Because the idea for the sensor is to work in industrial environments, specific in a power transformer plant, for the communication a wireless protocol was selected. The XBee modules, based on ZigBee communication protocol, were the selected devices for the project. These modules provide an easy installment and simple configuration, fulfilling all the technical requirements. They work with the technical features of 2405-2480 MHz as frequency range, 540 kbps as speed rate and a reach scope of 100 m in open field. The biggest limitation would be the speed rate, but perfectly suitable for the proposed sensing application within this project.

The physical installation of the communication hardware system will be composed of:

- Two Arduino One boards
- Two XBee antenna modules
- Two XBee shields for Arduino

There are two devices for each component, because there are two nodes composing the communication, so each node will have one of each. All these components will have to be adapted to the sensor and computer needs for the installation, including its software configuration. The Arduino One microprocessor will require to be programmed in order to attribute it its occupation: to obtain the data from the sensor and transmit it to the antenna. The XBee modules will have to be programmed as well, identifying the different commands and assigning the address to the two nodes.

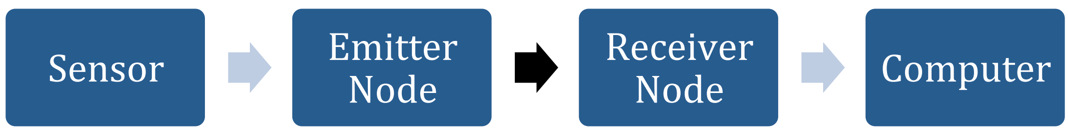

Figure 7.1. Communication distribution

These two nodes are the two points that compose the point-to-point communication, the emitter and receiver. The first one is connected to the sensor, and it will be responsible of obtaining the data from it and transforming it into a digital package that will be sent to the receiver node by the XBee module attached to the Arduino board. The receiver node will then obtain the sensor-emitted data and transmit it to the computer, where the information will be processed. The arrows on figure 7.1 indicate the connections, which are wireless for the black arrow and cabled in the blue arrows. Both nodes are composed of: 1 Arduino One, 1 XBee module and 1 XBee shield each.

7.1 ARDUINO

Arduino is a prototype electronic platform of open source based on a flexible and an easy-to-use hardware and software. It is composed of a simple plate with inputs and outputs that can be both analogical and digital. It can sense the environment through those input pins from a variety of sensors and can affect its surroundings by means of control options. The board includes a microcontroller that can be programmed with the Arduino Programming Language (Wiring) and Arduino Development Environment programs (Processing), both free to download from the Arduino main page. The projects the plate can develop can either be autonomous or communicated with execution software in a computer. Because it is an open source, both in its design and distribution, it can be used freely for the development of any project without needing any license.
The Arduino boards simplify the process to work with the microcontroller and when compared with other microcontroller platforms, it is relatively cheap.

The microcontroller composing the board is in charge of the logical and mathematical processes inside it. It also controls and manages the resources of each external component connected to the plate.
Arduino has the advantage of having as main parameters serial input/output ports, which allows connecting to a computer through a USB cable to work with it in the software level, where the external parts connected to the board will be assigned its commands or the plate will be set as a device.

The Arduino programming software [58] allows establishing the microprocessor´s procedure in order to acquire and control the sensor´s data. The programming language is based on the Processing platform and uses C/C++ language. This computer program is composed of a set of programming tools. This IDE (Integrated Development Environment) is a programming environment that has been packed as an application program, which consists on a code editor, a compiler, and a graphical constructor interface. In this case

it also includes tools to load a program already compiled from the hardware flash memory.
The program available from the main page and free to download is multiplatform, so it can be executed on any computer operative system and has a simple and clear programming environment.

The brand has different models, but in this project the nodes will be composed of Arduino One boards. These are based on the ATMega328 microcontroller and have 14 input/output digital pins, of which 4 can be used as PWM (Pulse-Width Modulation) outputs, 6 analogical inputs, a ceramic resonator of 16 MHz and a USB connector and reset button. The characteristics of this board are:

- Microcontroller: ATMega328
- Operative voltage: 5V
- Digital input/output pins: 14 (6 PWM outputs)
- Analog input pins: 6
- Flash memory: 32 KB (ATMega328)
- SRAM: 2 KB (ATMega328)
- EEPROM: 1 KB (ATMega328)
- Clock velocity: 16 MHz

The figure 7.2 illustrates the main electronic parts within the Arduino One board.

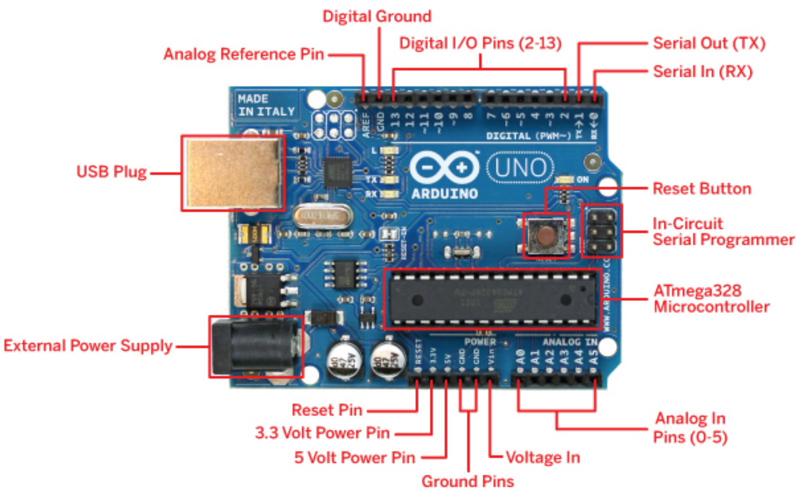

Figure 7.2. Arduino One board [59]

The Arduino One board can be powered though the USB cable connection or through an external power source, with voltage limits between 6 to 12 V, but with an operative voltage of 5V.

The Arduino software programs are called sketches, and are written on the computer and uploaded to the microcontroller for its work assignment. In the case of the project the two boards will be configured independently and in a different way, because each will be used as a different node on the communication link and so they have different objectives:

1. The emitter Arduino: the first node is referred to as the emitter. This one is connected to the sensor using one of the analog input pins. The microcontroller will then be programmed to "read" the input signal and transform the analogical value into a digital package.
   The conversion is done with the mathematical equation 7.1, taking into account the 10-bit Analog-to-Digital (ADC) converter included on the microcontroller ATMega328. The 10 bits indicate a resolution of 1024 values ($2^{10} = 1024$), from 0 to 1023. This means the maximum available digital value is 1023, while the analogical maximum is 5V. The lowest is 0 in both cases, but using the maximum values equivalency relationship it is possible to obtain the corresponding value from the sensor measurement.

$$Value_{digital} = V_0 * \frac{5}{1023} \quad (7.1)$$

   Once the information is held as a digital package, the XBee module attached to the Arduino board transmits it to the receiver. It repeats the process until the board is disconnected, but for efficiency purposes a timeout period was included, this means that it will wait a couple of seconds before acquiring the data and repeating the process.

2. The receiver Arduino: this plate will receive the information on the sensor. It is connected to the computer through the serial USB port, and will transmit the data automatically to it. The computer will have the designed interface (LabView program) opened and activated during the communication process; in this way it will obtain the information from the Arduino board and analyze it, in order to give the user the equivalent temperature.
   In this case the microprocessor does not need any software configuration, because it will have to be removed from the board. The desired communication is established between the computer and the antenna, and the ATMega328 will enable that communication.

The emitter will be powered from the same power source as the sensor, with 5V using the specific input voltage of 5V pin. It also needs to be connected to the ground, and so again, the same one as in the sensor will be used. Out of all the pins, only one analogical input pin is required. It can be any of them, but it is important to select one and always use the same one, because when programming microcontroller the used pin is specified, so it only "reads" that one. There are no more connections required.

The receiver node however will be powered through the USB port, which will be connected to the computer. Except for removing the microcontroller from the board, there are no other modifications or requirements for this Arduino plate.

7.2 XBEE MODULES

The XBee modules are manufactured by Maxstream, which belongs to DIGI INTERNATIONAL, as an adequate product for industrial use with a ZigBee protocol. They represent a solution for the wireless networks for its data communication applications. It makes all the communications through one channel out of the 16 available, and the reach depends on the transmission power of the device as well as the type of antennas used. For the particular modules of this project:

- The speed rate: 256 kbps
- Frequency band: 2.4 GHz
- Reach: 100 meter outdoors, 30 meter indoors
- Material: ceramic antenna

These modules allow the creation of a flexible network, with low cost and a low energy consumption; ideal for monitoring the environment parameters, such as humidity, light, sound, and like in this project case, temperature. The modules are responsible for finding their own communication path, assuring the most optimized option. The antennas have to be configured assigning an address name to each one and its working mode. Also the typology configuration and the network distribution have to be established. This is all done with the XBee module software, XCTU, previously explained in *Chapter 3 Wireless Communication Protocols*.

Because there are only two nodes composing the system (one emitter and one receiver) they will be using a point-to-point configuration. It is ideal for replacing the cable serial communication; it is only necessary to configure the address with the MY and DL commands.

The configuration of the XBee module allows two addressing types: of 16 bits or 64 bits. The main difference is that in the 64 bits, it is possible to obtain a greater quantity of addresses and so a greater number of nodes or equipment working on the same network. It is through the addresses that the modules communicate between one another.

In the 16 bit addressing the MY command is defined as a 16 bit number as address for the module in the network. The range goes from 0x0 to 0xFFFE (the addresses 0xFFFF and 0XFFFE are used for enabling the 64 bit address, so in a 16 bit addressing they cannot be used, neither for the MY nor the DL commands). To define the address the number is introduced in hexadecimal code, without the 0x. The DL command allows defining a 16-bit number as the destiny module´s address inside the network to which the communication will be made. The range goes from 0x0 to 0xFFFE.

The 64-bit addressing is activated when the values 0xFFFF and 0XFFFE are introduced in the MY and DL commands, respectively. When using this addressing mode it is not possible to define the addresses, neither for the origin module nor the destiny, and it is automatically assigned and will correspond to the serial number of the device, set by the manufacturer and impossible to change. The number is saved into two variables of 32 bits each (SL and SH) and it gives the module a unique "name". SL reads the 32 less significant values whereas SH the most significant ones.

When using a 64-bit addressing configuration the destiny address is set with commands DL and DH. Both are 32 bits and together form the 64-bits corresponding to the serial number of another module (SL+SH). This means DL must be equal to the SL and DH to the SH.

This project will be using the 64-bit configuration so the maximum number of net addresses available will be $1{,}18 \cdot 10^{19}$ (2^{64}), the same number of elements that can form the network.

For the point-to-point, previously mentioned, configuration the MY and DL commands will be used to indicate the origin and destiny address of the modules.

Because there are only two devices forming the network, it is not necessary to assign a coordinator role to any of them. Both will be working as end devices. The end devices do not have capacity to route packages and should always interact with another node, normally a coordinator.

The connection of the XBee antenna to the computer is done using the XBee shield, an extension to the Arduino board that allows connecting the XBee module and the Arduino by attaching its hardware. The antenna is placed on the shield that will then be introduced on the board through the pins.

Once the full communication system is set-up and all the components working together, the Arduino will be connected to the computer through the USB port and that will permit configuring the software parameters of the XBee module. The program XCTU has to be opened and once the system is connected, it should be able to recognize the antenna and then it allows starting its configuration.

Once the program has detected the RF modules the first parameters to be established are the determinants of the modules behavior, related to the serial communication between the nodes, table 7.1.

Baud Rate	9600
Data Bits	8
Parity	None
Stop Bits	1
Flow Control	None

Table 7.1. XBee module behavior parameters

After that, a specific configuration of each module has to be made. This configuration consists on establishing the origin and destiny address for both modules, and implementing the point-to-point transmission mode. Those addresses are established through the MY and DL commands, using the serial number of each one as their own address. In order to allow the communication it is required that both systems were on the same channel and net, referred to as the commands CH and ID respectively. This means that during the configuration these commands should have the same value. Each module is configured independently to each other, and the relationship between them is established with their designated addresses, setting them as origin/destiny on each of the set-ups.

- The emitter: the one placed next to the sensor design and the one in charge of obtaining the results and sending them to the other module. The XCTU configuration is done with a 64-bit addressing system, so the address names are the serial number of each module. This means the SH and SL commands are the name of the module. DH and DL are the composition of the destiny address, the other modules serial number in this point-to-point communication mode. The MY command has to be selected and different for each module, because it identifies the specific device, and so the emitter will be referred to as 1. And the last command is the operation mode, the CE command, which will be established as an end device, see table 7.2.

EMITTER	
Serial Number (SH)(SL)	13A200 40015BB2
Destination address (DH)(DL)	13A200 4001DD0B
Source Address (MY)	1
Coordinator Enable (CE)	End Device

Table 7.2. XBee emitter module commands configuration

- The receiver: this module will be connected to the computer, and will receive the information from the sensor and transmit it to the computer program. Because all the modules must use the same addressing technique, the receiver also uses the 64-bit. This means that its origin address is its serial number, and is the value on the SL and SH commands. The destination address, DH and DL, is the emitter's module serial number. Again, the MY command has to be assigned a value, different of the emitter one, so in this case, the receiver the MY will be 0. And as for the operation mode, the CE command, the module will be set as an end device, see table 7.3.

RECEIVER	
Serial Number (SH)(SL)	13A200 4001DD0B
Destination address (DH)(DL)	13A200 40015BB2
Source Address (MY)	0
Coordinator Enable (CE)	End Device

Table 7.3. XBee receiver module commands configuration

The rest of the parameters were set automatically by the firmware of the program, and they did not need to be modified, although it was checked that both modules had the same selections to assure the communication.

The point-to-point configuration can be observed on the two previous tables, because when observing the DH and DL for the emitter, there are the same values as the SH and SL of the receiver. The same happens when observing the parameters in the opposite manner.

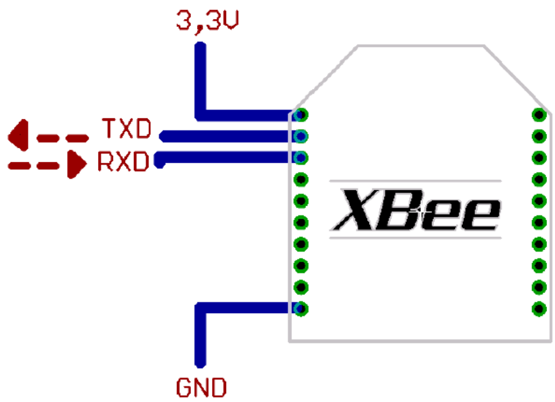

Figure 7.3. XBee module [60]

The XBee modules have two operation modes: the XBee and the USB position. The selection of one another depends on the hardware of the jumpers, observed on the image as T_X and R_X. These determine how the XBee´s serial communication connects to the serial communication between the microcontroller and the USB chip on the Arduino board; fig. 7.3 describes the main parameters of an XBee antenna, and its location on it.

The XBee mode will only be able to receive data from the XBee module, nothing from the computer through the USB. However with the USB position the XBee module will be able to communicate directly with the computer, but only if the microcontroller has been removed from the Arduino. This is because if the microcontroller stays on the board it will be able to communicate with the computer through the USB, but it will isolate the XBee module, and neither the computer nor the microcontroller will be able to communicate to the XBee module.

During the configuration of the software the module will be working on a USB position mode, because the antenna has to communicate directly with the computer in order to connect it to the XCTU program. The selection of each mode is done through hardware on the XBee shield platform.

7.3 XBEE SHIELD

The shields are circuit modular platforms that are assembled one on top of the other to give the Arduino extra functionalities. They are stackable, and allow enlarging the hardware and capacity of the Arduino is connected to.

They can communicate with the Arduino either through the digital or the analogical pins, or through a SPI (Serial Peripheral Interface), I2C (Inter-integrated Circuit) or serial port. They are powered by means of the Arduino through the 5 V and ground pins. Each shield must have the same form factor as the Arduino standard with the correct pin spacing, for a correct insertion.

When attaching the shield to the Arduino plate the digital pins from 2 to 7 and all the analogical ones will be covered by it, but it will provide those same pins on its own plate. The shield allows connecting the Arduino´s microprocessor with the antenna, or the antenna with the USB port, depending on the operation communication mode selected. This selection is done with the jumpers found on the shield.

These jumpers are connected to the R_X and T_X of both the Arduino and the XBee module, and depending on the selected mode the connections between them change. The selection is done using the XBee Shield hardware. The jumpers are small removable plastic sleeves that each fit onto two of the three pins labeled as XBee/USB.

Each communication mode will have different configurations, and so it will affect the system differently:

- XBee position: it makes a serial connection between the XBee module and the microprocessor in the Arduino (ATMega328).
  This means the pin D_{OUT} and D_{in} of the XBee module are connected to the pin R_X and T_X of the microcontroller respectively.

  The data from the microcontroller will be sent wirelessly through the XBee module using ZigBee protocol. This position also allows sending data from the module to the microprocessor. Figure 7.4 illustrates the schematics of the connections.

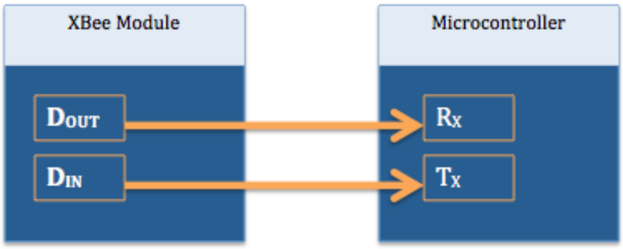

Figure 7.4. XBee position mode configuration

- USB position: it connects the microprocessor (ATMega328) with the USB cable.
  The pin D_{OUT} of the XBee module will be connected to the pin R_X of the USB converter, and D_{in} of the XBee module to the pin T_X of the converter chip, see fig. 7.5 for a schematic. This mode allows the XBee to automatically communicate with the computer, so it is the required position of the jumpers when establishing the plate configuration and addresses.

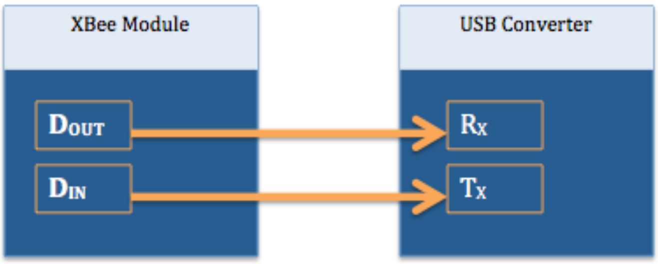

Figure 7.5. USB position mode configuration

In order to establish the communication between the computer and the module in both senses, the microprocessor has to be removed of the Arduino plate, otherwise neither the computer nor the microprocessor will be able to communicate with the XBee.

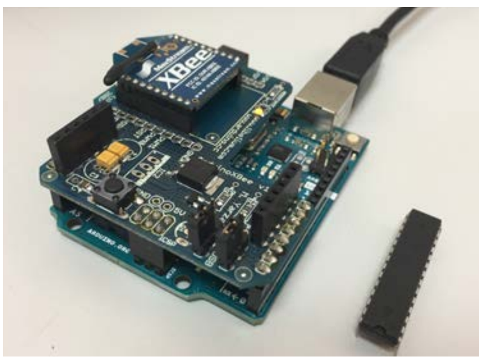

Figure 7.6. Full communication node

The figure 7.6 depicts a picture of the full communication node: Arduino board, with the XBee module on the shield and attached. In this case, the system is connected through the USB port, so the microprocessor was removed from the board, as it can be appreciated on the image, and the jumpers are on the USB mode, because the position of the jumpers leaves the two interior pins free.

Chapter8

COMPUTER INTERFACE

One of the main parameters of the system is the data analysis and interpretation. The sensor will measure the temperature information, which will be transmitted through a wireless protocol to the computer, where a program will be running with the user interface and data processing. The program used for this application is LabView,

LabView is a National Instruments integrated development environment specialized in industrial and scientific informatics. It uses a graphical language, called G Language. This means the programs are not written but designed with icons that represent different functionalities, joined together through cables that represent the data flow.

It permits the user to carry out process analysis, and data holding, distribution and representation using a graphic language following sequential lines. The programs are divided in two parts, the Frontal panel and the block diagrams:

- The frontal panel: is the user interface of the program, once the program is being executed is the one that holds all the information in real time, and allows the user to interact with the program. In this interface is where the controls and indicators will be defined. Referring to the input and resulting data respectively. It is also where the reactions to the data occur (light alarms are an example).
- The block diagram: it is the program where the functionality is defined, so where the icons will be placed and joined. Once the program starts running it cannot be modified or altered.

The programs are called Virtual Instruments (VI) because of its appearance and operation techniques, which imitate physical instruments such as oscilloscopes and multimeters. Each VI uses functions that manipulate the input data from the user interface and deploy and graph it, or move it to another file.

The most important advantage of LabView is that it is able to enable the communication with the Arduino board. It habilitates the ports and interfaces that sets this data transmission, and allows manipulating the data from the plate directly on the program. The communication is set using the specific Arduino functions found on the block diagram library, or through the expansion VI Package Manager that contain multiple resources and functions extra available to include on the VI when needed.

For this project, a LabView program will be created that will connect to the Arduino board through the USB port. The VI will open the serial communication between the two systems and start “reading” the received data from the module. That data will flow through the program, and reach the transformation function, which will take the digital package and convert it back into an analogical value. A second program will be created inside the main one, called Sub VI, which will have the calibration curve function, and will determine the relationship between the input voltage data and its corresponding temperature value. It includes two alarm systems, which will be activated when the value is outside the selected limits. These are visual alarms on the front panel, so that the user working with the program will see them when they are active. The process is generated on the block diagram window, and the final results will appear on the user interface.

Once the program starts running the VI activates the process explained, and will start giving the data to the user on the front panel window: the user will be able to see the exact temperature obtained from the sensor The process can be stopped at any moment because it includes a Stop button. It also includes an error analyzer, which will stop it automatically and give the user on the front panel a description of the anomaly detected.

The process of the data on the block diagram will follow a simple sequence, with functions lined one after another. The flow diagram describing it can be found below, fig. 8.1.

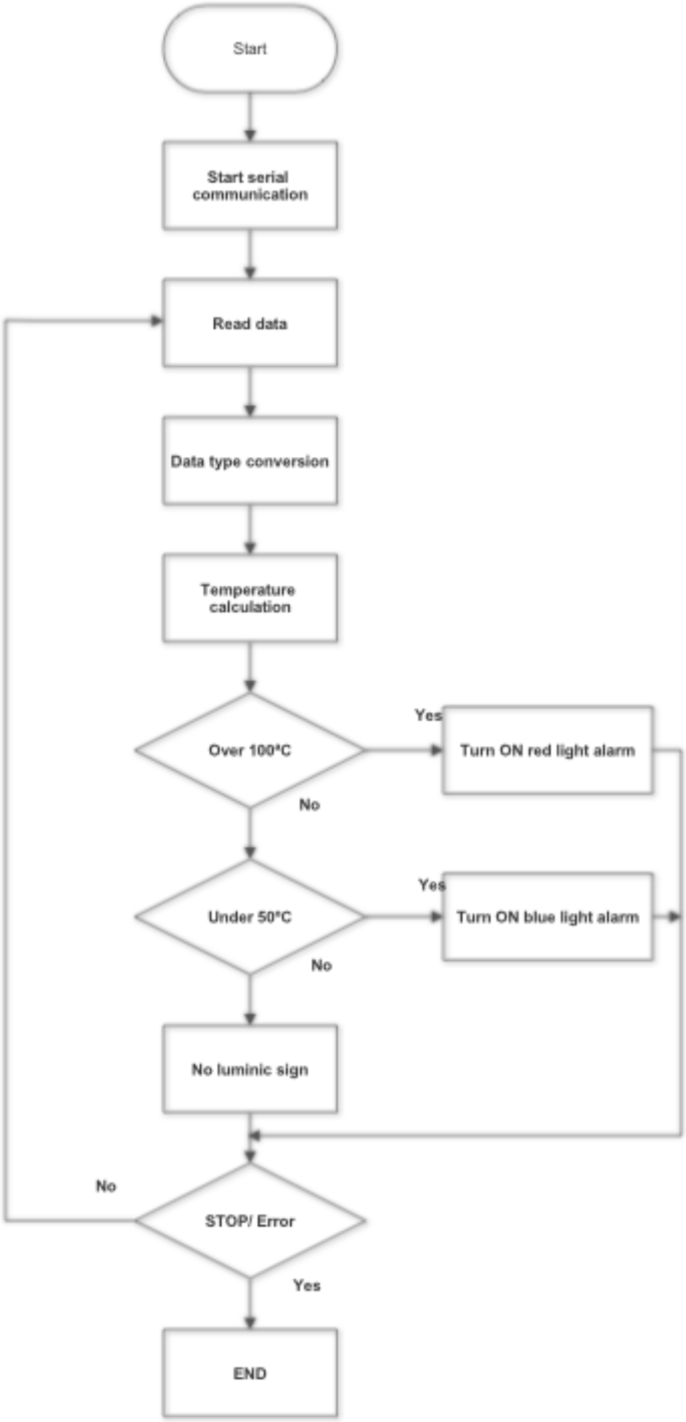

Figure 8.1. Flow diagram of the VI designed and implemented.

The following figure 8.2 shows a screenshot of the block diagram window of the created main VI. The square icons are the different functions composing the program, and are joined together through lines, which indicate the way the data is flowing. Some of the functions require extra data input to function. This means they need that information to set the parameters of the function. The program works from left to right. The stop button can be observed on the right bottom, and it is not connected to any other function, but when pressed will stop the process no matter where the data is.

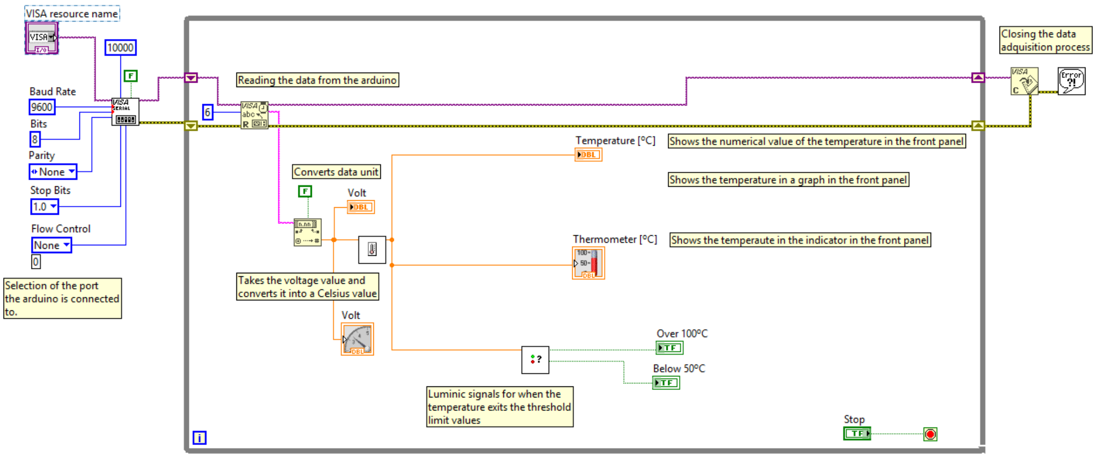

Figure 8.2. Block diagram of main VI

The program version used for this project was LabView 2016, the most updated of the National Instruments Company. This version simplifies the development to speed up the productivity. It simplifies the code to create the asynchronous communication. It also improved the object manipulation with a better dynamic selection. The error reports are more efficient, with a better understanding of each program, and the real-time process includes an actualization that improves the speed of the results.

The figure 8.3 below shows the block diagram again, but includes identifiers of the different stages of the program for a more detailed explanation. The order followed is the same as the data on the process; this means the sequential order of the functions.

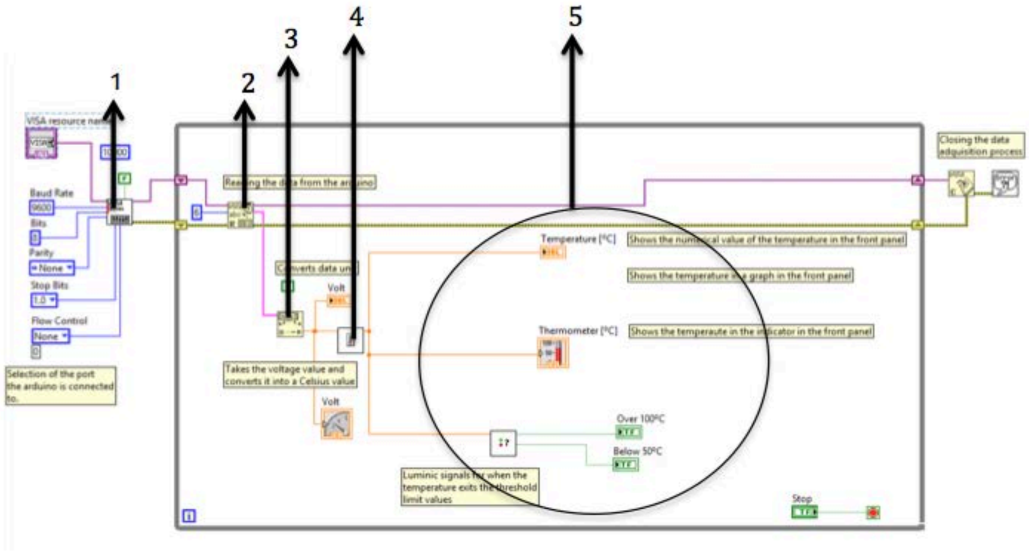

Figure 8.3. Block diagram of main VI referenced

1. The program starts with the **VISA Open** function, which initializes the serial communication between the program and the Arduino connected through USB. In order to know which port to read, before running the program it is essential to indicate the exact COM port the Arduino is connected to. This selection will be done through a control function found on the Front Panel, so the user will be responsible for it. This makes it a more flexible system, allowing to move the port if needed and including the program in different computers.
   The VISA function requires a specific configuration, which includes the communication parameters of the XBee module (the same parameters set during the XBee configuration).

   - *Baud Rate*: 9600
   - *Data Bits*: 8
   - *Parity bit*: None
   - *Stop Bits*: 1
   - *Flow Control*: None

2. Once the connection has been established the program will start reading the data. This next function is the **VISA read**, which will acquire the information from the board. It will understand it as a character chain.
   As a configuration requirement, the number of bytes that the function will read must be introduced. Knowing that the voltage value is a float variable type with a maximum of two decimals, it is equivalent to 6 bytes.

3. Up to this point the program is working with a char data type, so it must be transformed into an integer (numerical form) for its forthcoming analysis. LabView includes a **Data Converter** function, which allows this transformation.
   When the data enters the function it is read with a bit interpretation, the aim is to convert it into a numerical analogical value.
   The configuration includes the selection of the Boolean function as false, which indicates that the separation has to be understood as a point, because the desired result is a decimal value.

4. The data then continues as a number, and enters the following function that gives the equivalent temperature to the input value.
   This function is designed with a Sub VI specifically created for this project, called **Thermometer**.
   The input data is the voltage value from the sensor, and this function includes an equation 8.1, obtained from a calibration curve of the sensor, that gives the equivalent temperature to that input value. This means the output of the thermometer function is the temperature the sensor is being submitted to. The temperature parameter on the equation refers to the output data, and the voltage to the input value, the data obtained from the sensor.

$$Temperature\ [ºC] = Voltage\ [V] \cdot 191{,}06[{}^{ºC}/_{V}] - 658{,}75[ºC] \qquad (8.1)$$

   The design of the Sub VI will be explained later on this chapter.

5. The last stage of the VI includes all the indicators of the program. The indicators on the LabView platform are the output values of the functions, and will appear on the front panel for the user to see. They have informative purposes.
   There are different designs for the indicators: numerical, graphical… Because this project has a thermometer purpose, the temperature will be indicated with a thermometer design as well as a numerical screen.
   There is also an indicator for the voltage measurement, the data of from the sensor. And the program includes two visual alarm indicators. They are located after the temperature indicator, and are set to activate in case of being a value outside of the fixed limits. The first one will indicate when the temperature is too hot, above 100ºC and will have a red color when ON. The second one will have a blue color, and will work when colder temperatures, below 50ºC, are reached.

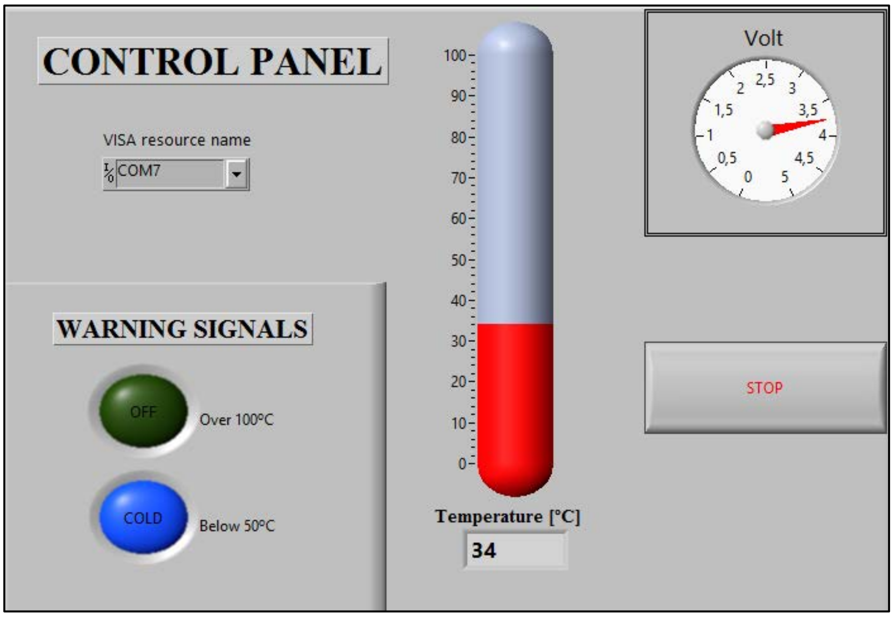

Figure 8.4. Front panel of main VI

The figure 8.4 is an image of the front panel of the VI, the user interface of the project.

The first parameter is the COM port control. It selects the port the Arduino board is connected to, for the function on the block diagram window. It is important to set this parameter before running the program; otherwise it will not be able to work.
The two warning signals are the visual indicators: of for temperatures greater than a 100ºC, and the other for temperatures below 50ºC. The image was taking with the program running, and because the temperature is 34ºC in the moments, the second indicator appears ON (blue light).

The clock on the upper right corner indicates the voltage value obtained from the sensor (the measurement of its output signal); this is the interpretation of the transmitted data,
The thermometer icon indicates the temperature the sensor is measuring, as well as the small screen below it that show the numerical values for an easier understanding. The temperature value is calculated using the voltage value on the screen and applying to it the equation obtained from the calibration curve.
The stop button is there in case it is necessary to stop the process. The action will proceed immediately when pressed.

8.1 THERMOMETER FUNCTION

The thermometer function is the Sub VI of the main program of this project. A Sub VI is a program generated as a VI, with its inputs and outputs that it is used in another VI as a function.

The main program of this project obtains the data from the Arduino board through the serial communication. Once entering the program, it follows a sequential flow where the information interpretation takes place, before the final analysis. This analysis consists on taking the voltage value from the sensor, and giving the user its equivalent temperature value (the temperature the sensor is being submitted to). There are no functions on the LabView library for this type of application, so it had to be created.

The Sub VI, referred to as Thermometer, takes the data from the Arduino board, when transformed into a numerical value, and gives the equivalent temperature for it on ºC. The conversion is done with a linear function obtained from a previous calibration of the sensor. This calibration consists on applying temperature variations to the sensor, and observing its effect on the output signal. The values will be recorded for the calculation of the function. The methodology for the calibration curve will be explained later on this chapter.

The following figure 8.5 is an image of the block diagram of the Sub VI. The "*Numeric in*" refers to the sensor data, the voltage value, and the "*Numeric out*" is the temperature result equivalent to the input value. The function includes a mathematical equation to obtain the equivalence.

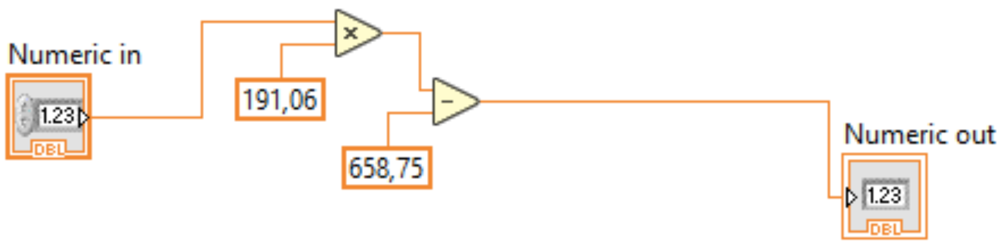

Figure 8.5. Block diagram of Sub VI (Thermometer function)

The front panel only has two small numerical screens, one for the Numeric in control and another on for the Numeric out indicator.

8.1.1 Calibration curve

The calibration curve corresponds to the collected values from the calibration of the sensor. The procedure consists on submitting the sensor to a variation of temperatures. This variation will affect the signal travelling through the sensor, so the final output result will depend on it. The response of the sensor to the different temperatures is collected and analyzed, creating the calibration curve for the system.

In order to do this measurement the sensor will be placed on a hot plate model LTS350 as the heat focus, which will provoke a temperature rise as a consequence to the variations introduced through the control unit module TP94, obtaining in this way the sensor's behavior with regards to different surrounding temperature values.

In order to measure the sensor´s response signal, it is not necessary to use the full wireless communication set up of the project. The Arduino One plates has analogical pins that will be connected to the output point on the circuit, and that same board will be connected to the computer through a USB serial communication.

The microprocessor will be removed from the plate, because all the instruction for the manipulation and acquirement of data from the Arduino board will be introduced with the LabView program. In order to do so a new VI was created, figure 8.6.

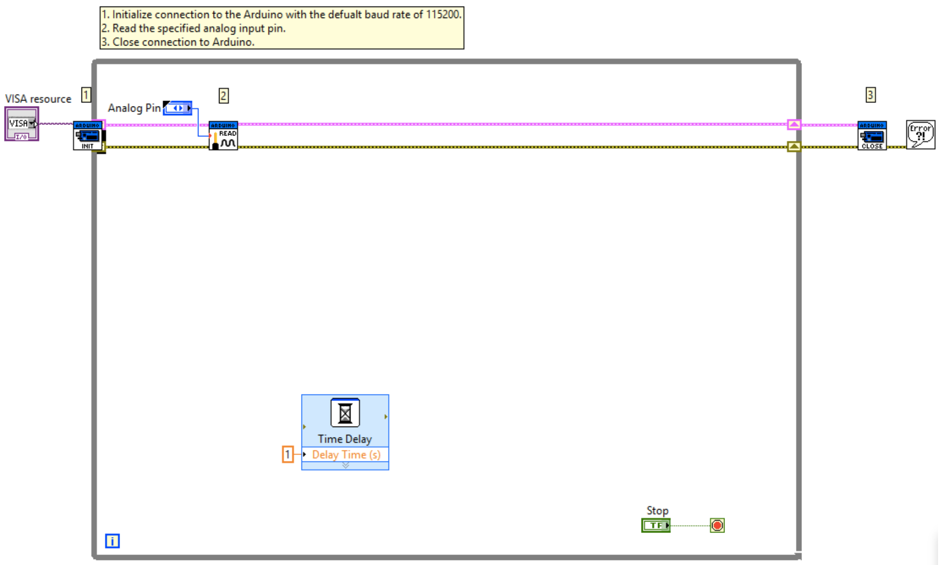

Figure 8.6. Block diagram of calibration VI

The figure 8.6 is an image of the block diagram of the new VI. It uses the Arduino tool kit, which enables the program to work directly with the board, is connected to. The COM port used for the connection must be selected. And the analogical pin being used on the Arduino plate has to be indicated to the program before running. This way it only reads the pin that has to. Both selections are made on the front panel of the program, so the user will set them before running the program.

In this case the Arduino functions do not require any extra configuration needed, the tool uses the default baud rate of 115200 (bps). Once the communication is set up, it starts reading from the analog pin in the Arduino plate. The data is automatically read as an integer data type (numerical values), so it was only necessary to use an indicator that will make the value appear in the front panel.

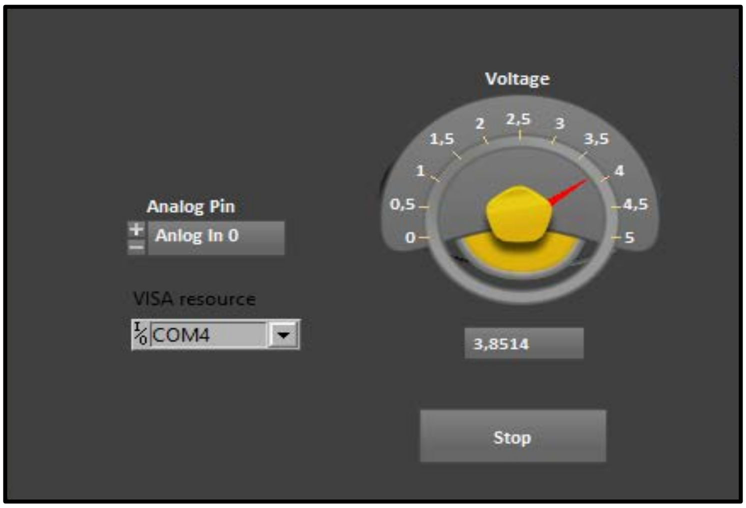

Figure 8.7. Front panel of calibration VI

The figure 8.7 is an image of the front panel of the VI. The two indicators are for the Arduino board parameters; to select the COM port the plate is connected to on the computer and the analog pin being used in the process. The numerical indicator and watch give the user the voltage value obtained from the output of the sensor.

The calibration of the sensor started submitting the sensor to a 30ºC temperature, and was carefully increased until reaching 70ºC in the heat plate. The obtained results from the calibration measurements are shown in the following table 8.1:

Voltage [V]	Temperature [ºC]
3,59	30
3,6	32
3,63	34
3,64	36
3,65	38
3,66	40
3,67	42
3,68	44
3,69	46
3,71	48
3,72	50
3,73	52
3,74	54
3,75	56
3,76	58
3,76	60
3,77	62
3,78	64
3,78	66
3,79	68
3,8	70

Table 8.1. Voltage and Temperature values from calibration curve

The voltage values were taken every minute, moment in which the temperature was 2ºC incremented. The voltage column stands for the values from the output of the circuit, and the temperature indicates the temperature the control unit displays, hence the temperature at which the hot plate is. These results were graphed in order to obtain lineal function that relates these results.

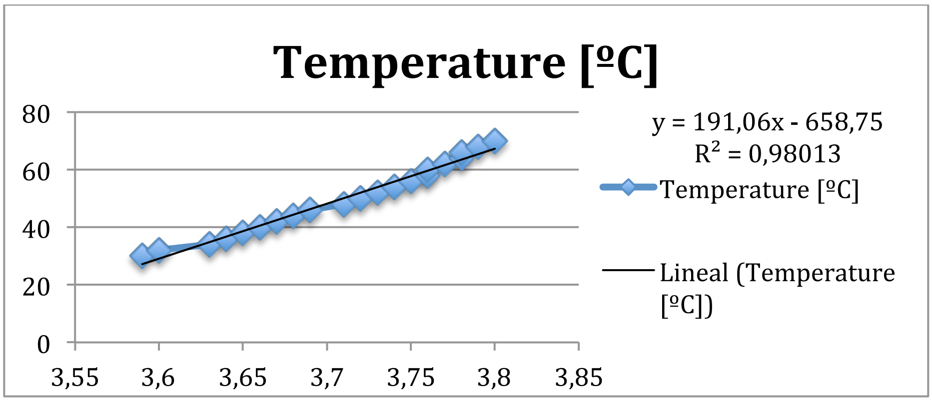

Figure 8.8. Temperature versus voltage

The fig. 8.8 shows how the linear growth of temperature in relation with the voltage. When one increases so does the other. The calibration curve is estimated following this growth, and determining the slope that characterizes. The equation on top right corner on fig. 8.8 shows the equation that meets the systems procedure.

Chapter 9

FINAL IMPLEMENTATION

The final implementation of the project consists on an operative temperature sensor with a remote monitoring using a wireless communication and a data analysis through a user interface. This includes the physical design of the sensor, with its adaptation to the transmission module. It also refers to the configuration of the communication process, establishing the routes and roles each module will have. And lastly, the creation of a computer interface program for the data interpretation and manipulation.

Once the system is activated, the final results are the temperature values of the transformer measured with the optical sensor. In order to obtain these values, the sensor is tested at different temperatures that are then evaluated with the interface.

The temperature variations around the optical sensor will be induced using a hot plate device. The selected one is the model LTS350 [61], a heating and cooling system with fast heating up rates up to 50ºC/min and thermal stability. It consists on a heated sample area of 53mm x 43mm, which is a sample chamber with gas tight and features gas valves to enable purging with inert gas or flow of humidified air. This plate is connected to a control unit TP94 [62] that enables to externally set the temperature of the plate, also allowing the variation of the value.

The optical sensor will be placed with the exposed part on the hotplate, as observed on figure 9.1. When inserting the plate it will be turned off, and it will not start working until the communication is activated and the interface starts running.

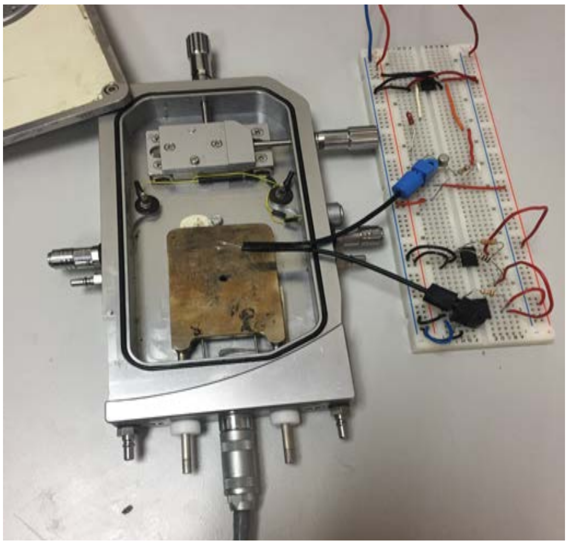

Figure 9.1. Sensor physical system

Once the optical sensor is located on the hot plate and the chamber closed, the power source is activated, feeding with 5 and -5V. This will activate the sensor circuits and the Arduino board connected to it.

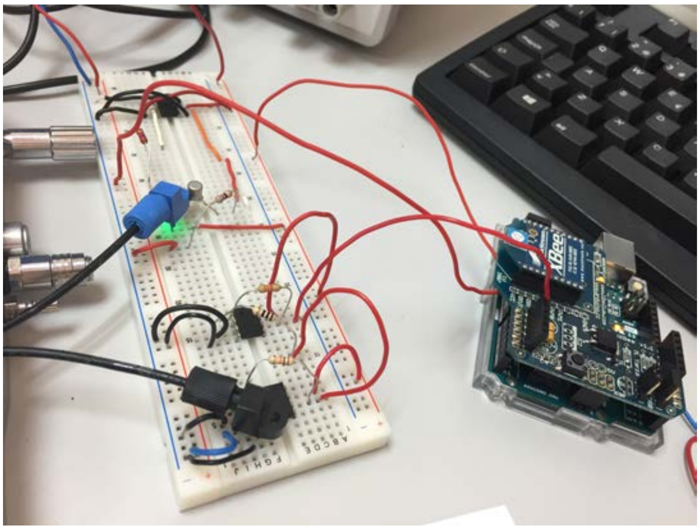

Figure 9.2. Emitter node physical system

Figure 9.2 shows a picture of the emitter communication node. It includes the sensor circuit and the Arduino board with the XBee shield attached to it. The wires coming out from the Arduino are the three required connections, the powering, which will be done at 5V and ground, and the analogical pin (A_0) to the output point of the circuit system. The following table 9.1 indicates all the parameters and the configuration of the emitter communication node. The pins relationship indicates the name of the pin from the Arduino plate and what is connected to.

Emitter Node	
Arduino One	
Pins:	5V → from power source
	GND→ power source
	A0 → V_0
XBee Shield	Attached to Arduino
Jumpers	XBee position
Address	1
ATMEGA 328	Programmed with Arduino software

Table 9.1. Emitter node parameters

Once the Arduino is connected to the source system it automatically starts the transmission. The second communication node, composed by the second Arduino board and XBee modules is connected to the computer through the USB. This connection works as a power source for the Arduino board, and activates the communication with the emitter node. The table 9.2 indicates the configurations of the parameters composing the receiver communication node.

Receiver Node	
Arduino One	
Power source→	USB port
XBee Shield	
Jumpers →	XBee position
Address→	0
ATMega328	Removed

Table 9.2. Receiver node parameters

It can be observed how the table 9.2 indicates that the microprocessor (ATMega328) of the Arduino board has to be removed. This is because the communication between the computer and the plate use a serial connection, and if the microcontroller is left on neither the computer nor the plate will be able to communicate with it, and so the data transmission will no be finalized.

Once the communication is established the LabView interface takes over the execution of the process. This means, the program controls the Arduino plate, and the data received from the emitter node is transmitted through the serial USB port to the program, for its analysis. The interface will start studying the information on the sensor and giving the equivalent temperature value for it. The fig. 9.3 is an image of the full-implemented system.

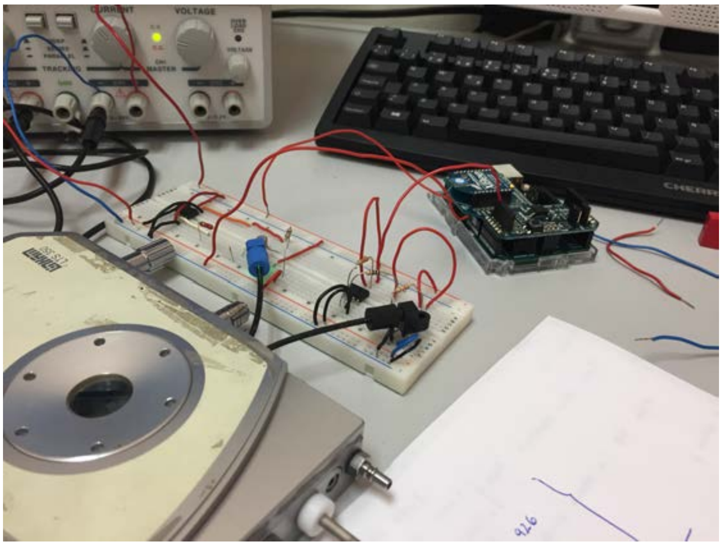

Figure 9.3. Complete physical system

9.1 RESULTS

The complete system was designed and built on the DTE lab facilities, where it was also tested. The testing process consisted on the alteration of the temperature of the hot plate and observing how the sensor reacted to those changes. The variation of the temperature the sensor is exposed to, reflect on the signal response. This means that the different temperatures should give different output signal values.

Table 9.3 provides a compilation of the testing process experimental results. The first column (Control Unit) indicates the value that appears on the screen of the TP94, hence the temperature of the hot plate. The second column (LabView) gives the results appearing on the user interface on the computer, and should be equivalent to the values on the first column. The third column (Voltage) is the data values being transmitted from the sensor. The ones the LabView program uses to obtain the equivalent temperature.

Control Unit [ºC]	LabView [ºC]	Voltage [V]
30	28	3,56
35	34	3,589
40	40	3,625
51	46	3,77
56	50	3,79
64	60	3,81
71	68	3,83

Table 9.3. Temperature testing results

The results obtained assure the system is working as desired. The sensor is being submitted to different temperatures, and the signal response varies along with it. The data acquisition process shows no failure while running, and the transmission process works smoothly. The computer interface receives the data and analyses it at the set time, giving responses almost immediate to the measurements from the sensor.

It can be observed that there is a small change between the temperature the hot plate is set to, and the one given by the program. This can be due to different factors; the calibration curve for instance may be one of the reasons, because the relationship between the signal and the temperature does not follow an exact linear tendency. It can also be due to some losses while running the different processes, because it is not working under ideal circumstances, and there might be noise or other factors affecting them. However, the obtained results show an efficient system, because the difference between the temperatures is no more than 6ºC, which allows a correct interpretation of the temperature frame on the sensor.

9.2 POWER OVER FIBER RESULTS

The application of the power over fiber as a remote power source was tested on the sensor system after it was fully implemented and verified it was working correctly.

The power over fiber technology used was the PhD project previously mentioned. The topology design implemented on the power over fiber uses a connection with shared power. Its objective is sharing the optical power of one PPM (Photonic Power Module) to feed multiple PPC (Photovoltaic Power Converter). It is a useful topology when the electrical power demanded by the PPC is low. The system uses a power divider so that each PPC can obtain a fraction of the optical power from the PPM.

Before replacing the source power with the PoF, the power consumption of the instrumentation system has to be checked, in order to guarantee the PoF covers the system necessities, which has a maximum of 500 mW available.

When studying the system for the power balance, it was decided to modify the design. The sensor is powered by +5V and -5V, which is not optimal for the PoF implementation because it uses 10V to power the system. This new design will reduce the power source to +5V, and will use an integrated that will take that power and inverse it, giving a -5V source.

The integrated used is the MAX889T model [63] from the Maxim industry. This system takes the input charge and gives as an output its inverted value. This means the designed system will maintain the required +5/-5 V charge, but instead of coming both from the same source, the MAX889T will give the negative value. The electronica will now have a consumption of 130 mA, which is fully covered by the MAX889T, which can hold up to 200mA.

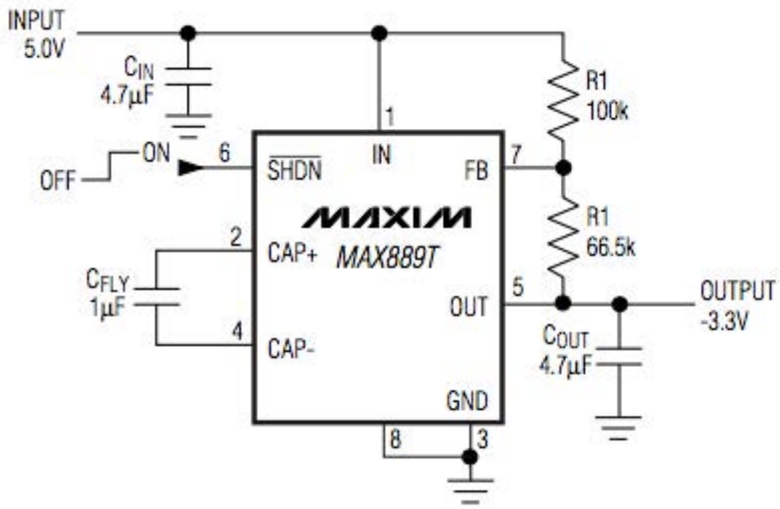

Figure 9.4. MAX889T application system [63]

The adaptation of the integrated to the system includes the implementation of the design on fig. 9.4. The capacitor values will remain the same in both cases, but the resistances will be modified and replaced by $\mathbf{R_1= R_1= 50k\Omega}$ (following the referenced parameters on the circuit). This implementation was not integrated, and has to be designed experimentally. Figure 9.5 is an image of the full-developed circuit.

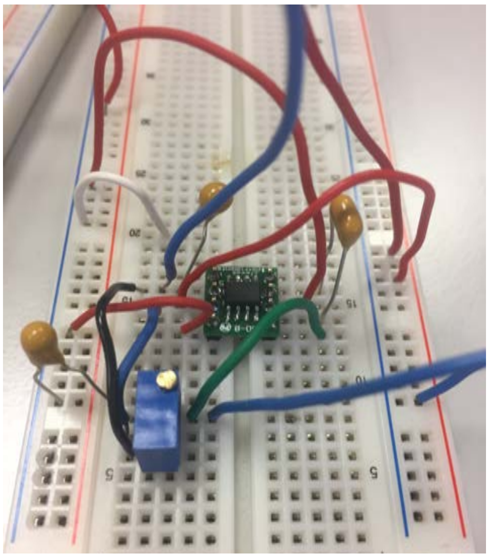

Figure 9.5. MAX889T circuit implementation

Once the full assembly of the system is done, see fig.9.6, including the MAX889T circuit, the required power charge will be +5V and it will have an estimated consumption of 130mA. The PoF will be then connected as the source, and will use 25 m and 100 m.

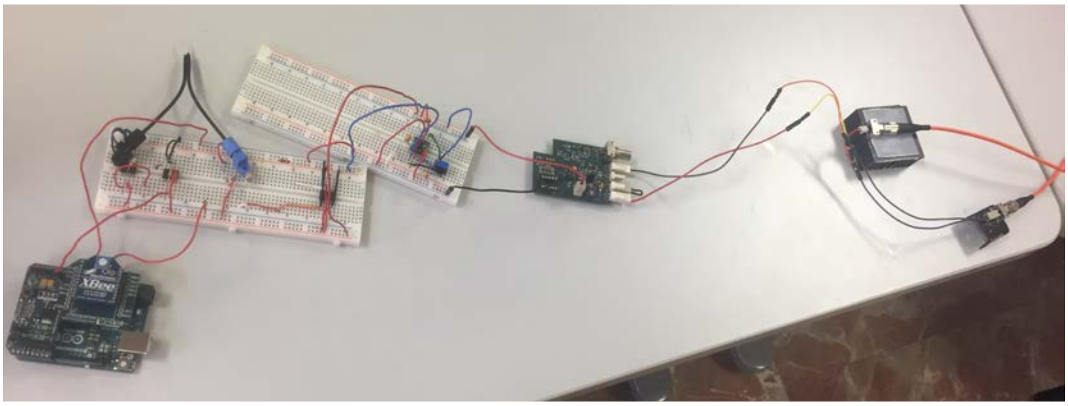

Figure 9.6. Sensor system powered by PoF

The schematic of the PoF follows the design on fig 9.7 and 9.8. The difference between one another is the lengths of the cables, which is determined on each case. The Tx stands for the laser device (SPL 2F81-2S), the light travels through the fiber, (represented by straight lines), and the small squares are the photovoltaic converters, responsible of providing the electrical source to the system.

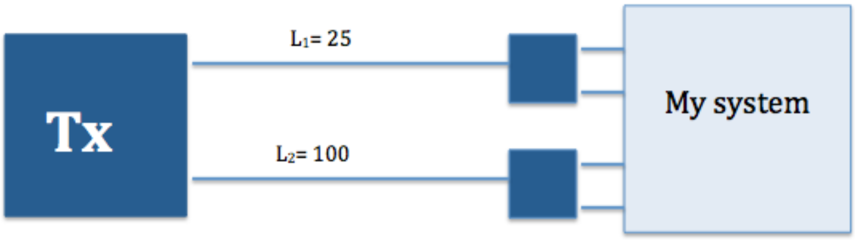

Figure 9.7. PoF schematics of modality 1

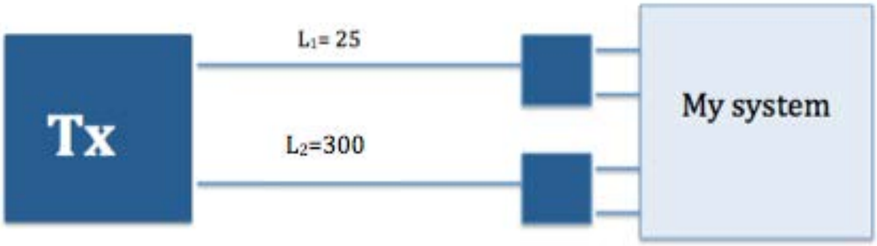

Figure 9.8. PoF schematics of modality 2

The main characteristic of using the PoF as power source for the system is the immunity to the electromagnetic interferences. This will be an advantage for this project, which is set to work on hostile environments. The available PoF technology had to be adapted to meet the consumption requirements of the sensor system.

The available laser works with an emission optical power of 1,5W, which does not fully reach the PV cells, because of the losses of energy from external factor and the attenuation of the fiber. Each cell can provide up to 6V if working as it maximum, so in order to guarantee the consumption of the system, and reach the required 5V, 2 PV cells were placed parallel to one another. This design increases the output power in case only one source is not enough for the required power.

The PoF was tested on the system to observe its efficiency, and using the power balance equations from *Chapter 4: Power Over Fiber* (equations 4.1 and 4.2), it is possible to estimate the electrical power inferring on the system. This calculation take into account the attenuation parameters of the fiber. Because it is working with a power of 805nm of wavelength, the fiber will have losses of 19dB/km (α). As external factors, only the connections at both ends of the fiber were taking into account, with an estimated attenuation of 0,5dB (α_{conv}) at each end.

Two different models were tried out for this system, illustrated on figures 9.7 and 9.8. The difference between them is on the length of the fibers. The first model (fig. 9.7), uses L_1=25 m, and L_2=100 m, and its power balance calculations are:

$$Att_{L1}(dB) = 19\left({dB}/{km}\right) \cdot 25m + 2 \cdot 0{,}5(dB) = 1{,}47\ dB \tag{9.1}$$

$$Att_{L2}(dB) = 19\left({dB}/{km}\right) \cdot 100m + 2 \cdot 0{,}5(dB) = 2{,}9\ dB \tag{9.2}$$

The attenuation for model 1 is calculated using equation 4.2. There are two factors for the same model, because each fiber has its own, based on the length of the cable. The losses parameters are the previously mentioned for this PoF system.

Knowing the attenuation factor of each fiber (eq. 9.1 and 9.2), and that the HPLD used for this test is working with an emission optical power of 1,5W (P_{in}), the optical power entering the PV cell (P_1) can be estimated from equation 4.1. Again, because there are two fibers, there are two source points (P_{outL1} and P_{outL2}). These two values will be added to know the total power received on the PV (P_{out1}).

$$P_{outL1}(dBm) = 31{,}76\ dBm - 1{,}47\ dBm = 30{,}29dBm \tag{9.3}$$

$$P_{outL2}(dBm) = 31{,}76\ dBm - 2{,}9\ dBm = 28{,}86dBm \tag{9.4}$$

Which in watts units is:

$$P_{outL1}(mW) = 10^{P_{out}(dBm)/10} = 10^{30{,}29/10} = 1069\ mW \tag{9.5}$$

$$P_{outL2}(mW) = 10^{P_{out}(dBm)/10} = 10^{28{,}86/10} = 769{,}13\ mW \tag{9.6}$$

The calculated power on equations 9.5 and 9.6 represent the power the PV cell can emit on the system, but it must be taken into account that the cell device work with a limited capacity, this is the efficiency of the device, which for the available PV cells is estimated to be 42%. This means the actual power emitted on the system is:

$$P_1(mW) = P_{outL1} \cdot 0{,}42 + P_{outL2} \cdot 0{,}42 = 772\ mW \tag{9.7}$$

The second model tested uses the same parallel PV cells design, but replaces the L_2=100m fiber with a L_2=300m fiber. The L_1=25m remained constant, this means its attenuation value matches the one calculated on equation 9.1 ($Att_{L1}(dB)$) and so does the power entering the PV cell (P_{outL1}), equation 9.5. The attenuation and power for the L_2=300m fiber is:

$$Att_{L2-2}(dB) = 19\left({dB}/{km}\right) \cdot 300m + 2 \cdot 0{,}5(dB) = 6{,}7\ dB \tag{9.8}$$

$$P_{outL2-2}(dBm) = 31{,}76\ dBm - 6{,}7\ dBm = 25{,}06dBm \tag{9.9}$$

$$P_{outL2-2}(mW) = 10^{P_{out}(dBm)/_{10}} = 10^{25,06/_{10}} = 320,62\ mW \tag{9.10}$$

So the inferring electrical power (P_2) on the system using the second model, is:

$$P_2(mW) = P_{outL1} \cdot 0,42 + P_{outL2-2} \cdot 0,42 = 583,64\ mW \tag{9.11}$$

The values P_1 (eq. 9.7) and P_2 (eq. 9.11) represent the power, on each model, the cells are feeding the system. The sensor requires 5V as source, which was what the PoF´s parameters were set to generate. However, the consumption may not meet the requirement of 130mA. The following equations calculate the consumption of each model applying equation 9.12, and knowing the voltage of 5V.

$$P(W) = V(V) \cdot I(A) \tag{9.12}$$

$$I_1 = \frac{P_1}{5V} = \frac{772mW}{5V} = 154,4mA \tag{9.13}$$

$$I_2 = \frac{P_2}{5V} = \frac{583,64mW}{5V} = 116,72mA \tag{9.14}$$

These results theoretically prove that the second system tested (eq. 9.14) does not meet the consumption requirement of 130mA, so it cannot be used as a power source. However the first model, with a consumption of 154,4mA is able to generate enough power to activate the sensor system. This means that using two fibers of L_1=25m and L_2=100m the system from this project could work using PoF, avoiding any electromagnetic interference.

After the calculations, the two models were tested on the system.

The first modality tested, the fig.9.7, with L_1= 25m and L_2= 100m worked correctly, and it was able to power the sensor system with enough energy to keep it active. Proving the theoretical results. However, the second modality, fig. 9.8, with L_1= 25m and L_2= 300m, was not enough to charge the system, it did not provide the minimum energy required and so the sensor was not operative.

This means only the first model will work for this project, being able to provide the system enough energy to start running, however this method requires greater amounts of energy, and bigger installation, and even though one of the cables measures 100m, it is limited to a maximum 25m distance.

Because the aim of the sensor is working on hostile environments, the necessity of a system fully immune to electromagnetic interferences may be a requirement. This will mean the use of PoF as a power source. The following calculations will estimate the maximum length the fiber may have, in order to meet all the parameter requirements of the system.

These parameters are: a voltage of 5V and a consumption of 130mA. With these parameters the power required, applying equation 9.12, is:

$$P = 5V \cdot 130mA = 0{,}65W \qquad (9.15)$$

For this design, the PoF is going to use only one PV cell that, because it has a maximum of 6V, is able to generate the required 5V. The minimum length of the fiber for this case is:

$$Att(dB) = P_{in}(dBm) - P_{out}(dBm) = 31{,}76\ (dBm) - 28{,}12(dBm) = 3{,}68\ dB \qquad (9.16)$$

$$L(m) = \frac{Att(dB) - \alpha_{conv}(dB)}{\alpha(\frac{dB}{km})} = \frac{3{,}68\ dB - 2 \cdot 0{,}5(dB)}{19(\frac{dB}{km})} = 0{,}14\ km = 140m \qquad (9.17)$$

The equation 9.16 calculates the minimum attenuation of the PoF, with the power emitted from the HPLD and the minimum power the system must receive in order to work. Once the attenuation factor is identified, applying equation 4.1 (power balance equation from *Chapter 4*), it is possible to determine the minimum length. The fiber parameters remain constant, because the PoF technology will be the same, this is 19dB/km losses from the entering power wavelength and 0,5 dB at each end of the fiber.

The project´s system was designed with a 5V source requirement, which in case of powering using the PoF technique working with a HPLD emitting 1,5 mW and a wavelength of 805nm, will need a minimum length of the fiber of 140m (eq 9.17).

Chapter 10

BUDGET

Code	Unity	Description	Quantity	Unitary Price	Total Price
		Chapter 1: Material			
01.01	Uty	**Resistance** 10Ω, 1/W tolerance 5%	1	0,02 €	0,02 €
01.02	Uty	**Resistance** 3,3kΩ, 1/W tolerance 5%	1	0,02 €	0,02 €
01.03	Uty	**Resistance** 2,7kΩ, 1/W tolerance 5%	1	0,02 €	0,02 €
01.04	Uty	**Resistance** 82Ω, 1/W tolerance 5%	1	0,02 €	0,02 €
01.05	Uty	**Resistance** 10kΩ, 1/W tolerance 5%	1	0,02 €	0,02 €
01.06	Uty	**Operational Amplifier** Brand ST microelectronics. Model TL081, with voltage ranges from 15 V to -15 V for input and from -18 V to 1V of source, and a maximum power of 680mW	3	0,20 €	0,60 €
01.07	Uty	**Bipolar BJT transistor** Bran Phillips, model 2N2222 with a maximum current of 800 mA and a power dissipation of 500mW.	1	0,10 €	0,10 €
01.08	Uty	**Optical emitter** Brand Industrial Fiber Optics, model IF-E93, with a 522 nm of wavelength and currents up to 35 mA, with a standard cable connection of plastic and a core of 1mm.	1	3,00 €	3,00 €
01.09	Uty	**Optical fiber** Plastic multimode fiber with an index jump with 1mm diameter and 2,2 mm jacket.	1m	1,00 €/m	1,00 €
01.10	Uty	**Photodetector** Brand Industrial Fiber Optics, model IF-D91, with an spectral range from 450 to 1050 nm and a plastic standard cable connector of optical fiber, with a nucleus of 1mm and cladding of 2,2mm	1	3,00 €	3,00 €

01.11	Uty	**Arduino board** Arduino board, model Arduino One, with microcontroller ATMega328, USB connector standard type B female and external source connector of 9V.	2	36,00 €	72,00 €
01.12	Uty	**XBee module** Wireless communication transceptor for the standard radiofrequency IEEE 802.25.4 of the brand DIGI International. Model XBee series 1, of 25 mm2, 1 mW of power and 40 mA of operation current.	2	14,00 €	28,00 €
01.13	Uty	**USB cable standard type B** Cable to two USB ports at both ends.	2	4,00 €	8,00 €
					115,80 €

Code	Unity	Description	Quantity	Unitary Price	Total Price
		Chapter 2: Computer Software			
02.01	License	**Arduino IDE** The open-source Arduino Software (IDE) makes it easy to write code and upload it to the board. It runs on Windows, Mac OS X, and Linux. The environment and other open-source.	1	0,00 €	0,00 €
02.02	License	**XCTU** From the DIGI International brand. It is a multiplatform application compatible with Windows, MacOS and Linux. Graphical network view for simple wireless network configuration and architecture. API frame builder is a simple development tool for quickly building XBee API frames. Firmware releases Notes Viewer allow user to explore and read firmware releases.	1	0,00 €	0,00 €

02.03	License/ Year	**LabView 2016** Software from the National Instruments industry. LabView software is ideal for any measurement or control systems, and it is heart of the NI design platform. Integrating all the tools that engineers and scientist need to build a wide range of applications in dramatically less time, LabView is a development environment for problem solving accelerated productivity and continual innovation.	1	400,00 €	400,00 €
					400,00 €

Code	Unity	Description	Quantity	Unitary Price	Total Price
		Chapter 3: Instrumentation Tools			
03.01	Uty	**Power Source** Power source brand Thurlby Thandar Instruments, model EL302Tv, with two outputs of 0 and 30 V, one output of 1,5 and 5 V and currents from 0 to 2A	1	420,00 €	420,00 €
03.02	Uty	**Multimeter** From brand Amprobe, model 37XR-A, with maximum currents of 10 A (AC) and 750 V (AC).	1	180,00 €	180,00 €
03.03	Uty	**Power Source Connector** Jack Connector 5,5X2, 1 mm	1	5,00 €	5,00 €
03.04	Uty	**Temperature Control Unit** TP94, brand Linkam Scientific Instruments, controllers capable of not only precision temperature controls, but also moving precision stepper motors, displaying data from high resolution force transducers, humidity and gas sensors and data streaming on to a live video feed.	1	150,00 €	150,00 €

03.05	Uty	**Temperature Hot Plate** LTS350, brand Linkman Scientific instruments, are easy to use heating and cooling systems, with fast heating rated up to 50ºC/min and excellent thermal stability from -196ºC to either 350ºC or 420ºC. With ah heated sample are of 53mmX43mm, and swing-out lid it is ideal for larger samples, and can be used with samples mounted on standard microscope slides.	1	325,00 €	5,00 €
03.06	Uty	**Computer** Personal computer with operative systems compatible with the software programs used. (Windows).	1	600,00 €	600,00 €
					1.360,00 €

Code	Unity	Description	Quantity	Unitary Price	Total Price
		Chapter 4: Personnel			
04.01	Hrs.	**Junior Industrial Engineer** Design and implementation of a sensory system, including its adaptation in a wireless network and development of a computer interface.	504	45,00 €/h	22. 680,00 €
					22.680,00 €

The cost of the Engineer is calculated taking into account the estimated period of time for the development of the work, the total of business days in the working time and the workday for the engineer. Once knowing the exact number of hours used and the cost per hour, it is possible to obtain the total cost for the project of the engineer.

Estimated time for the development of the project [Months]	Working days/month	Work day [hours/ day]	Total hours employed	Cost per hour [€/hr.]
4	21	6	504	45,00 €

BUDGET SUMMARY

	DESCRIPTION	TOTAL COST
Chapter 1	Material	115, 80€
Chapter 2	Computer Software	400,00€
Chapter 3	Instrumentation tools	1.360,00€
Chapter 4	Personnel	22.680,00€
	Total	24.555,80€
	IVA (21%)	5.156,72€
	Total offer (IVA included)	**29.836,72€**

The Budget of the total offer (without IVA) amounts to twenty four thousand five hundred and fifty five euros with eighty cents.

Chapter 11

CONCLUSION AND FUTURE WORKS

11.1 CONCLUSION

This project had different objectives, with the main purpose of creating an instrumentation sensor system and its adaptation into a wireless network, with the design of a nice and simple interface as control unit to be implemented in hostile industrial areas taking advantage of the use of an optical fiber sensor, which guarantees immunity to the electromagnetic and radiofrequency interferences. This small description means the design, development and integration of the different technologies involved.

For the monitoring process of the sensor the system uses wireless devices and computer programs, which contribute to a fast reading of the data collected. And the possibility of working in a wireless environment that provides mobility and flexibility, with a system with low price and low consumption.

Based on the description of the system and the objectives set, the conclusion will be that the 4 initial established objectives of the project have been met,

The first one is the selection of an optical fiber sensor. This can be verified in *Chapter 2 Temperature Sensors*, when comparing the different options and its characteristics. This sensor habilitates the possibility of working with the sensor placed inside of a power transformer, without the risk of damaging neither of the devices and avoiding the electromagnetic interferences. The selected components that go along with sensor fit the criteria as well, using a LED and photodiode adapted to the fiber employed, and with materials able to work under high temperature conditions, as observed on *Chapter 6 Sensor Design.*

The second objective is the communication protocol selected. The ZigBee standard adapts to all the necessities and creates a wireless network ideal for industrial applications, such as power transformers plants, which is the aim of the project. *Chapter 3 Wireless Communication* can verify this selection, because it is based on the comparison of the available protocols, and their characteristics. ZigBee adapts to the project nicely and habilitates the possibility of increasing the network if necessary, providing a flexible network at a reasonable low-cost. The use of the XBee modules assure the low price and low consumption of the devices, and work as providers of this protocol, and are adaptable to the desired environment. So the objective of the wireless network was fulfilled with the selection of the XBee modules and Arduino boards, as can be seen on *Chapter 7 Communication Design*.

The third objective is the creation of a computer interface for the data analysis. In many instrumentation projects one of the main purposes is the interpretation of the information. The created computer interface provides a method of collecting data and obtaining the final result, which enables the possibility to study the sensed area in real time. This can be observed in *Chapter 9.1 Results*, where the sensor was exposed to different temperatures

and the interface was able to react to it and give the user the new result. The variations were made abruptly to confirm the sensor system was correctly established.
The forth objective was the final achievement of a system with low price and low consumption. This means all the selected components and devices on the final system fulfill these objectives. The communication devices selected maintain a low price and are competitive products in the market, as well as the consumption, which assures a long active life for the full system.

Once finalized the design and implementation of the system, and after testing it is rightfully functioning, it can be assured that the set objectives have been satisfactorily fulfilled, and the implementation of a sensorial network has been achieved, also allowing the possibility of a future increase of the project providing it with flexibility.

Some secondary conclusions are the agility and skills personally obtained on all the used elements for this project. The different software programs had to be mastered in order to be used this includes the configuration of the components such as the Arduino board or the XBee module among others. Also, it was required a previous theoretical knowledge of the functioning of the sensor and its components before its design, this refers to the circuits and the criteria's for the selection of the sensor.

11.2 FUTURE WORKS

This part of the project presents suggestions for future extensions and works that based on lack of time have not been carried out in this.

One of the main features of the sensorial networks is its flexibility. This means it provides the opportunity of increasing and modifying the net, including more sensorial devices or replacing them if necessary. A possible improvement of the system would be the incorporation of more sensors to this network, which will enable the user to monitor more parameters on the same transformer, such as humidity, pressure…
A different approach to the increase of the network, could be locating a temperature sensor on more than one transformer unit or at different spatial locations within the same transformer unit, and monitoring all of the sensors from the same interface. Giving the user a more detailed analysis of the transformers state.
Another possible expansion for the project is the incorporation of individual batteries for each sensor, which will work as power sources. This advancement will reduce the size of the system, and will provide the opportunity of locating the sensor on smaller and difficult areas to reach

within the industrial machine. This will be also an advantage, because it will create an autonomous device.

If incorporating the mentioned batteries, it would be advisable to include some monitoring system of its energy levels. This will guarantee a control over its operative life, and will avoid any failures based on power source.

This project included the replacement of the power source for a PoF method. It was proved that this method would work on the system, even though it was not designed specifically for it. An advancement of the project could be designing a new temperature sensor adapting it to the complete requirements of the PoF, to obtain the most optimized system possible.

The main focus of this project was the installation of the sensor on power transformer plants, which makes it ideal for hostile industrial environments. This means this same sensor design could be adapted to any factorial industry desired, which require monitoring at high risk.

Chapter 12
REGULATIONS

There are different regulations that must be taken into account in implementation of the project, considering the different processes included in it.

Because it uses a wireless communication protocol, as its transmission procedure it is important to take into account that in order to incorporate wireless communication into the project there are two options. It can either be integrated in the circuit board of the own device to develop, or a module including all the necessary elements can be bought. The advantage of the second option is that all the modules are already tried out and usually include all the regulation certificates. This simplifies the certification of the final product integrating the communication.

Another important aspect of the wireless communication is the operation frequency. By law, the use of electromagnetic spectrum is normally restricted and requires licenses and concessions. There are, however, exceptions. The Scientific and Medical (ISM) or Short Range Device (SRD) is frequency bands known as industrial bands. They are internationally used for the free applications in communications, and are specified by the Federal Communications Commission (FCC) in the United States, or the European Telecommunication Commission Standard Institute (ETSI) in Europe.

The ISM And SRD more frequent European bands are frequently used in wireless device with a short/medium range:

- ISM 433 MHz (433, 05-434, 79 MHz)
- SRD 868 MHz (863-870 MHz)
- ISM 2,4 GHz (2,4-2,835 GHz)

These bands are defined by the regulation of ETSI EN 300, and taking into account that the bands do not require licenses for each business that uses them, are the most suitable for this project.

The industrial security is an essential factor to take into account when working in any industrial process, to guarantee the protection of the people, the flora, fauna and environment. This project is aimed to work with power transformers, which are included in the mentioned processes. The following Spanish laws and decrees establish the main applicable regulation, which includes the national quality infrastructure and security on power transformer plants.

- *Real Decreto 337/2014*, of 9th of May, by which approves the regulation on technical conditions and safety guarantees in electrical high power tension installations and its Technical Complementary Instructions ITC-RAT.
- *Real Decreto 228/2006,* of 24th of February, by which there are, established the measurements for elimination and management of polychlorinated biphenyls, polychlorinated terphenyls and apparatus containing them.

- *Real Decreto 614/2001,* of 8th of May, by minimal provisions for the security and health protection of the workers against the electrical risk.

Chapter 13
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[63] *High-Frequency Regulated 200mA Inverting Charge Pump,* Maxim, China, 2000

ANNEX

ANNEX 1: LabView

The following annex will include a compilation of all the windows forming the programs used in this project from the LabView resource. This programs are called virtual instruments (VI) and are composed of two different interfaces:

- Block diagram: where the programming takes place. LabView uses a graphical language (G), so the configuration of the interface will be done using different icons representing functions. It uses a sequential methodology, with the data flowing through the joins, visualized as wire unions. This will be observed on the following images.
- Front panel: the user interface. This will be the window the user will use to interact and manipulate the data. Once active it cannot modify the sequence of the data.

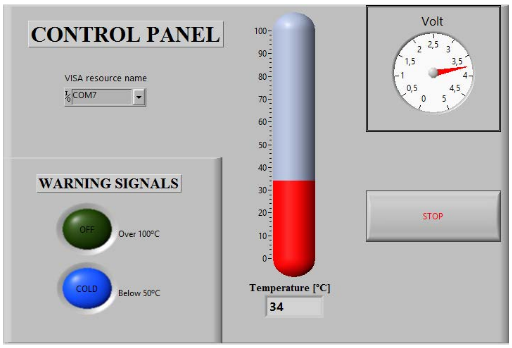
The program version used in this project is LabView 2016, obtained from the National Instrument official webpage.

Four programs were developed for this project:

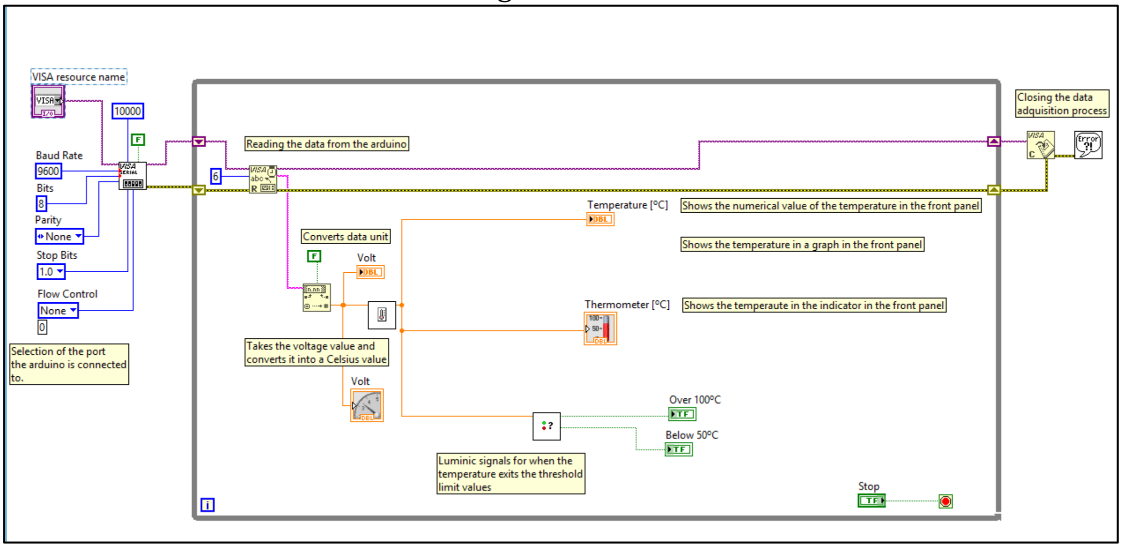
1. Main Virtual Instrument: it is the main interface of the sensor. Designed for the monitoring of the temperature the sensor is exposed to. It gives the user the exact value of the temperature, and the data value obtained from the sensor output. It includes two alarm signals, set to activate when the temperature is outside the limits set.
2. Thermometer Virtual Instrument: this will work as a Sub VI on the main VI; this means it will be a simple function inside the programming. It is designed to convert the data value from the sensor into the temperature value applying the lineal function obtained from the calibration,
3. Alarm Virtual Instrument: it will also work as a Sub VI on the main VI. This program is configuring to activate an alarm when the temperature is out of the limits.
4. Calibration Virtual Instrument: This is the program use to read the reaction of the sensor to the variation of the temperature. The values obtained were graphed in order to obtain a lineal function that gives the equivalency between the output signal and the temperature submitted.

The following figures are the images of the described Virtual Instruments, including both components:

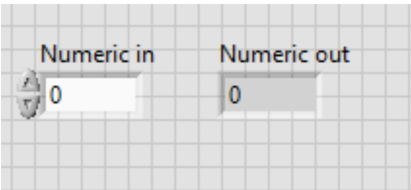
Main Virtual Instrument: Frontal Panel



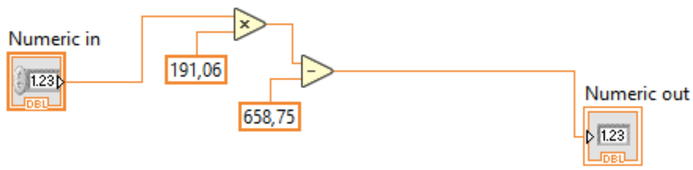
Main Virtual Instrument: Block Diagram



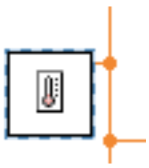
Thermometer Virtual Instrument: Frontal Panel



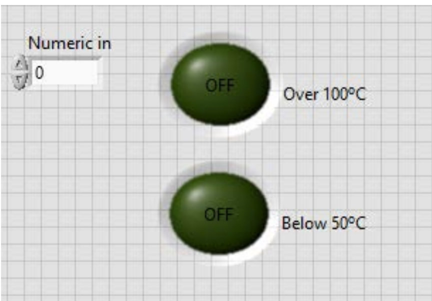
Thermometer Virtual Instrument: Block Diagram



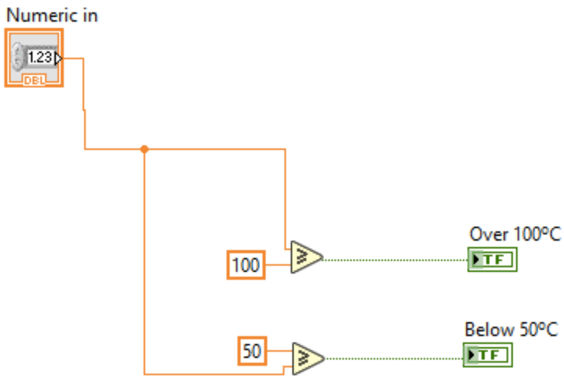
Thermometer: Sub VI icon



Alarms Virtual Instrument: Frontal Panel

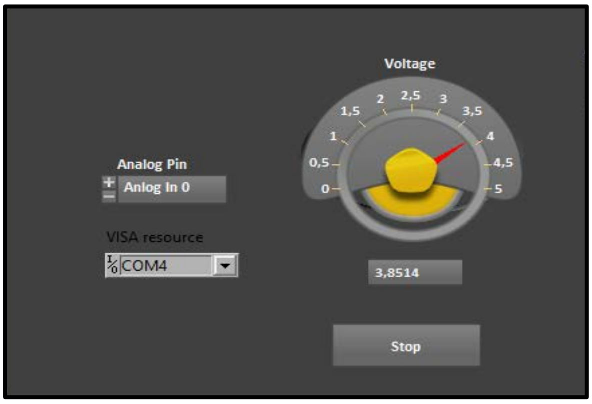


Alarm Virtual Instrument: Block diagram

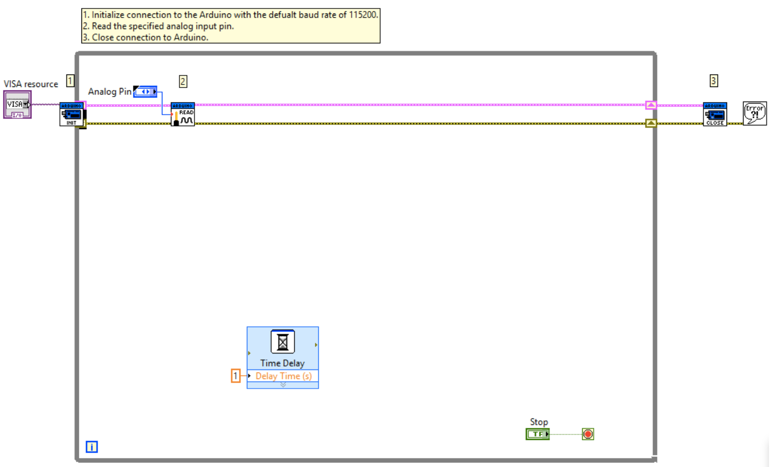


Alarm: Sub VI icon

Calibration Curve Virtual Instrument: Frontal Panel



Calibration Curve Virtual Instrument: Block diagram

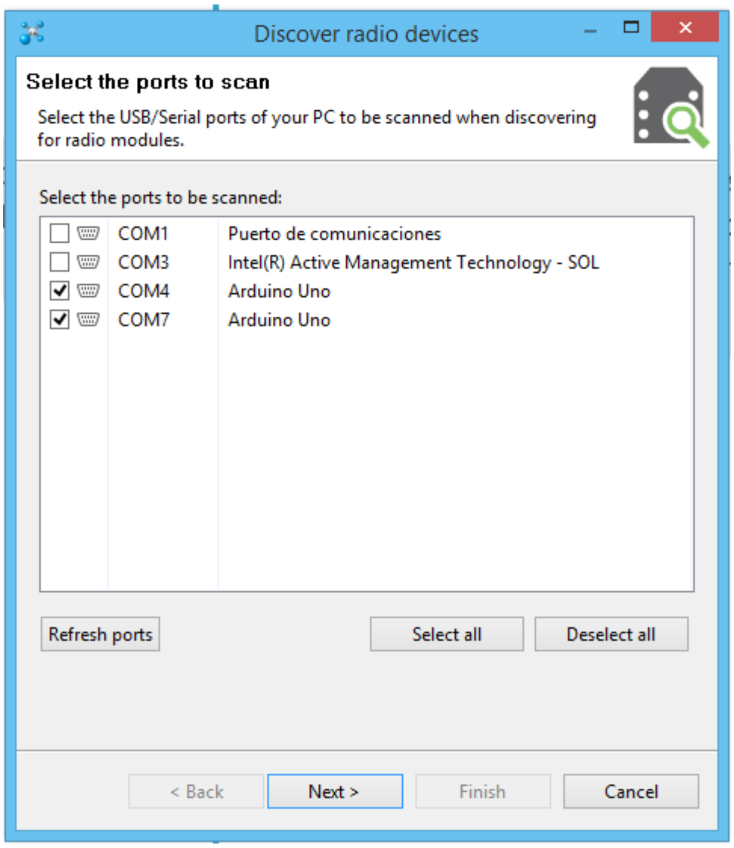


ANNEX 2: XCTU

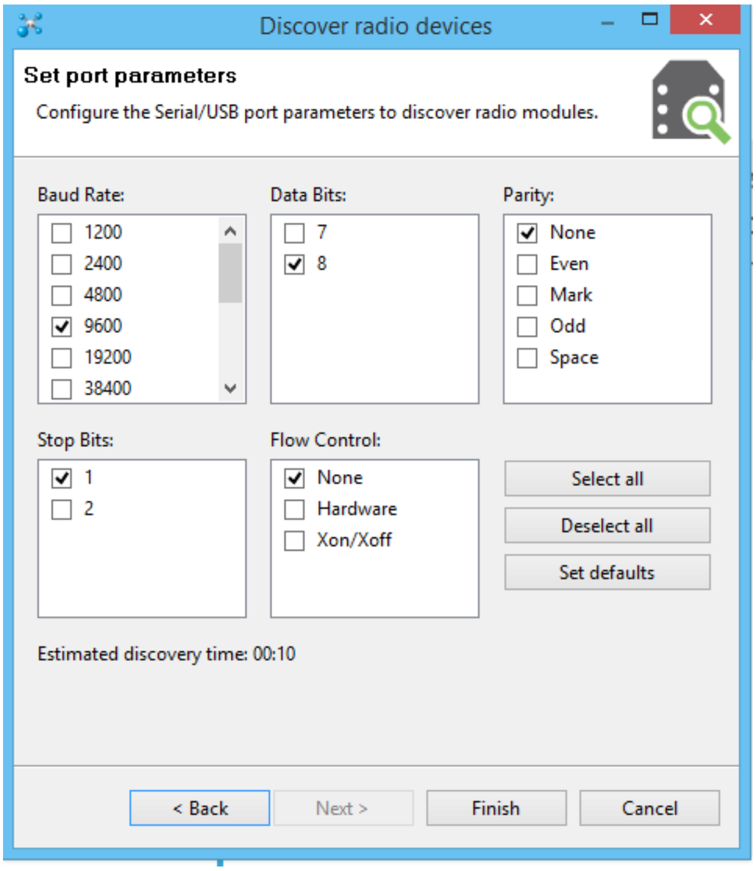
The program XCTU is obtained from DIGI main webpage, and can be downloaded free. The installed version was the latest on the market: XCTU v. 6.3.8 Windows x86/x64.

The first step is to plug in the XBee modules to the computer. This will be done using the Arduino One board and its USB serial connection. The XBee will be attached to the plate with the XBee shield.

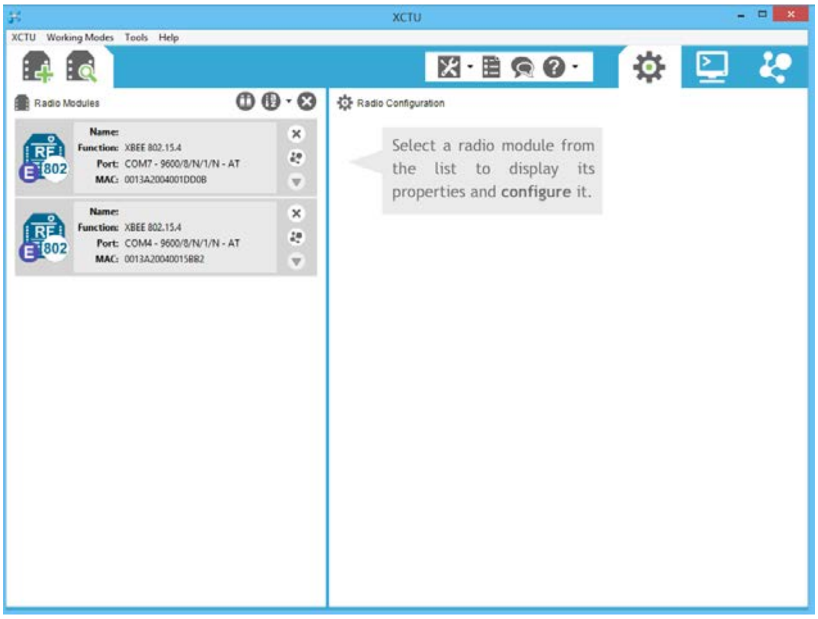
Once the module is connected to the computer XCTU software is executed. The program will then find all the radiofrequency devices plugged to the computer. The selected modules are the ones the program will be working on. For this step is important to distinguish the COM port the module is connected to. When done, the user clicks “Next”.



The following step is the selection of the radio modules main parameters. This configuration includes the selection of the main characteristics of the data and communication process.

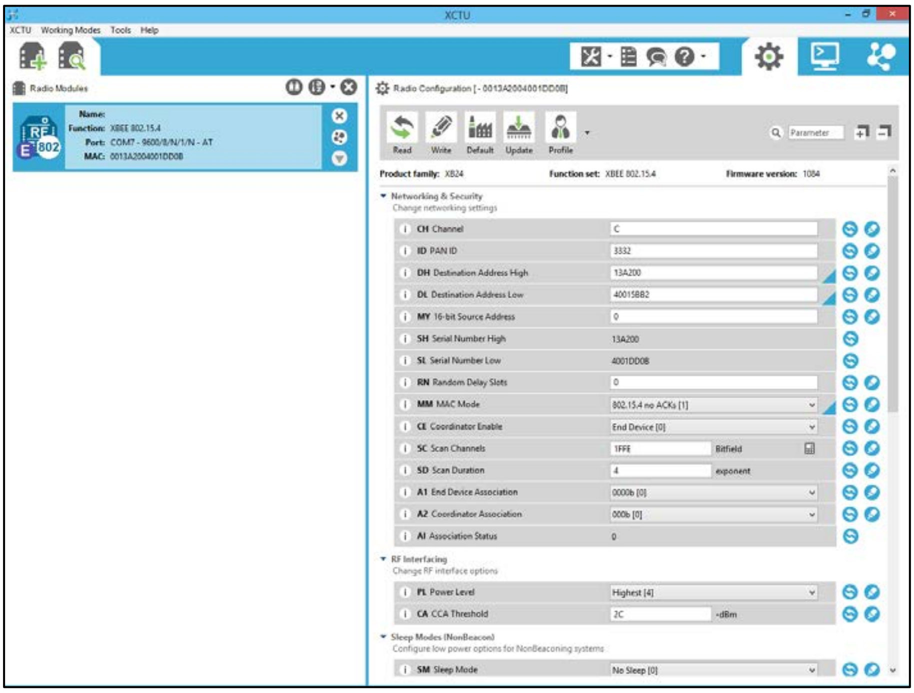


Once the parameters are selected, the following step is to establish the commands of the modules. In this image both used modules appear on the screen, in order to work with one it is important to select it.

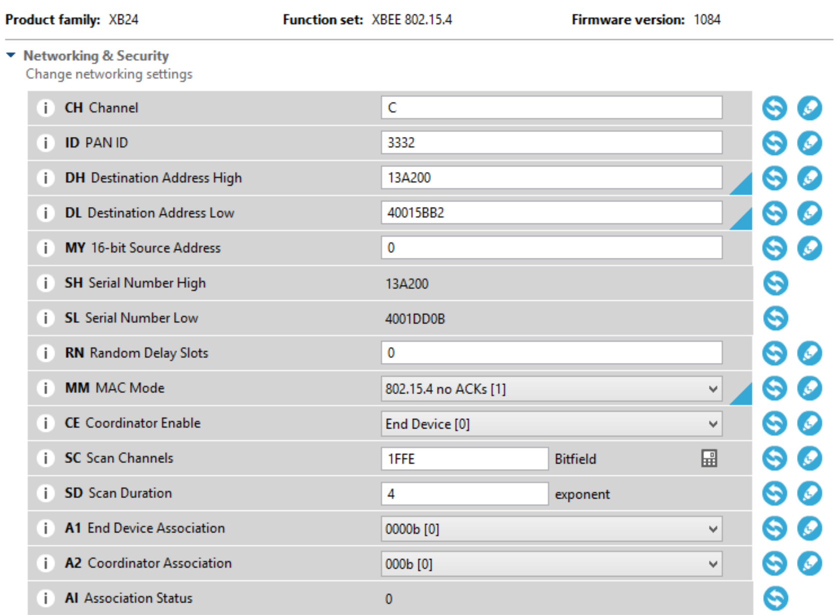


The last step is the configuration of the commands. Because the firmware was actualized to its latest version, and both modules have the same, the only

parameters that had to be set were the destiny address, each other address and the MAC module, which was set to no ACK.
Because in this the modules work with a 64 bits addressing the address name was the serial number of the components, and it used two commands of 32 bits each in the case of the destiny address DH, DL.



The following images are a more close up picture of the commands of one of the modules. Because the network is composed of only two components, the only difference between one another is the addresses. This means that what in one module is SH, SL in the other is DH, DL, and the other way around. The other parameters were kept from the firmware configuration of the modules.



Product family: XB24 **Function set:** XBEE 802.15.4 **Firmware version:** 1084

- Networking & Security
- RF Interfacing
  Change RF interface options

PL Power Level	Highest [4]	
CA CCA Threshold	2C	-dBm

- Sleep Modes (NonBeacon)
  Configure low power options for NonBeaconing systems

SM Sleep Mode	No Sleep [0]	
ST Time before Sleep	1388	x 1 ms
SP Cyclic Sleep Period	0	x 10 ms
DP Disassociated Cyclic Sleep Period	3E8	x 10 ms

- Serial Interfacing
  Change modem interfacing options

BD Interface Data Rate	9600 [3]	
RO Packetization Timeout	3	x character times
D7 DIO7 Configuration	CTS flow control [1]	
D6 DIO6 configuration	Disabled [0]	
D5 DIO5 configuration	Associated indicator [1]	
P0 PWM0 Configuration	RSSI [1]	
AP API Enable	API disabled [0]	
PR Pull-up Resistor Enable	FF	

Product family: XB24 **Function set:** XBEE 802.15.4 **Firmware version:** 1084

- Networking & Security
- RF Interfacing
- Sleep Modes (NonBeacon)
- Serial Interfacing
- Diagnostics
  Access diagnostic parameters

VR Firmware Version	1084	
HV Hardware Version	1742	
RP RSSI PWM Timer	28	x 100 ms
DB Received Signal Strength	0	
EC CCA Failures	0	
EA ACK Failures	0	

- AT Command Options
  Change AT command mode behavior

CT AT Command Mode Timeout	64	x 100ms
GT Guard Times	3E8	x 1ms
CC Command Sequence Character	2B	Recommended...x7F (ASCII)

ANNEX 3: Arduino

The Arduino Software was obtained from the Arduino main web page, and was free downloaded.

The software allows writing the code and then uploading to the microprocessor on the board. This annex includes the Arduino codes used for the project and the images of the computer program.

In order to test the Arduino plates were working correctly, the first code was a testing code, obtained from the examples on the program, which made the light on the board blink.

```
//Blink Code. Calibration
// the setup function runs once when you press reset or power the board
void setup() {
  // Initialize digital pin LED_BUILTIN as an output.
  PinMode(LED_BUILTIN, OUTPUT);
}

// The loop function runs over and over again forever
void loop() {
  digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on (HIGH is the voltage
level)
  delay(1000);                       // wait for a second
  digitalWrite(LED_BUILTIN, LOW);    // turn the LED off by making the voltage
LOW
  delay(1000);                       // wait for a second
}
```

The following code was the one implemented into the microprocessor ATMega328 on the Arduino board connected to the emitter node of the system. This node was the one connected to the sensor, which is in charge of obtaining the data from the sensor transmitting into the XBee for its emission.

```
//Arduino Emitter Code

#include <avr/io.h>
float SensorValue =0;

int voltage=0;

void setup() {
  Serial.begin(9600);
}

void loop() {

  voltage= analogRead (A0);
```

```
    SensorValue= voltage*(5.0/1023.0);

    if(Serial){
     Serial.println(SensorValue);
    }

   delay(100);
   }
```

This is an image of the Arduino Software page, where the program was written and check. In order to upload it into the board the Arduino has to be connected to the computer. The COM port check has to be selected on the software, and after that clicking the arrow button on the top of the page can upload the program.