



**Universidade de
Aveiro**

2014

Departamento de Eletrónica, Telecomunicações
e Informática

**Rui Pedro Lebreiro
Gomes**

**Sistema de Localização Fina para Ambientes
Interiores**

**Fine-Grained Localization System for Indoor
Environments**



**Rui Pedro Lebreiro
Gomes**

**Sistema de Localização Fina para Ambientes
Interiores**

**Fine-Grained Localization System for Indoor
Environments**

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Rui Escadas, Professor auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e do Professor Doutor José Fonseca, Professor associado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro e do Professor

Dissertation submitted to the University of Aveiro in the fulfilment of the requirements for the degree of Mestre em Engenharia Electrónica e Telecomunicações, conducted under the supervision of Rui Escadas, Professor auxiliar at the Departamento de Electrónica, Telecomunicações e Informática of the University of Aveiro and co-supervision of José Fonseca, Professor associado at the Departamento de Electrónica, Telecomunicações e Informática of the University of Aveiro.

Dedicado a todos aqueles que me acompanharam neste percurso

O júri

Presidente

Professor Doutor Paulo Bacelar Reis Pedreiras

Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Vogais

Professor Doutor Valter Filipe Miranda Castelão da Silva

Professor Adjunto da Escola Superior de Tecnologia e Gestão de Águeda da Universidade de Aveiro

Professor Doutor Rui Manuel Escadas Ramos Martins

Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

agradecimentos

Foram muitos os que, das mais diversas formas, colaboraram para realização deste projecto. Não posso deixar de agradecer a todas estas pessoas que deixaram a sua contribuição, quer a nível científico quer a nível emocional e motivacional, e sem a qual a conclusão desta dissertação não teria sido possível. Gostaria de começar por agradecer ao meu coorientador, Dr. José Fonseca, pela proposta do tema que desde o início me suscitou bastante interesse, pela sua orientação nas alturas de maior indecisão e pela confiança que depositou em mim ao longo de todo o percurso. Agradeço ainda ao meu orientador, Dr. Rui Escadas, pelo auxílio prestado nas questões técnicas e por toda a disponibilidade demonstrada e ainda ao meu parceiro de trabalho e amigo Samuel que me acompanhou no desenvolvimento deste trabalho.

Não poderia também deixar de agradecer aos meus pais por impulsionarem e apoiarem todo o meu percurso académico. Eles que sempre acreditaram nas minhas capacidades e sempre demonstraram confiança e apoio nas minhas decisões. Foram os valores e a educação que eles me transmitiram que fizeram de mim a pessoa que sou hoje. À minha irmã, namorada e amigos deixo também um especial agradecimento por me terem aturado e incentivado nos momentos menos bons.

Por fim deixo os meus agradecimentos à Micro I/O Serviços de Electrónica, LDA pela cedência dos uMRFs que foram indispensáveis para a realização deste projecto.

palavras-chave

Real-time Locating System (RTLS), Indoor Positioning System (IPS), Time Difference of Arrival (TDOA), Rastreamento, Ultra-sons, Radiofrequência, IEEE802.15.4, Comunicações sem fios, Microcontrolador, Triangulação

resumo

A crescente demanda por soluções de rastreamento em ambientes interiores levou ao desenvolvimento de vários sistemas de localização baseados nas mais diversas tecnologias. Eles vêm tentar colmatar um nicho de mercado deixado pelos sistemas de localização actualmente disponíveis como o caso do bem conhecido Sistema de Posicionamento Global (GPS). Estes sistemas estão limitados ao uso exterior devido à drástica atenuação dos sinais GPS em áreas fechadas e eles não oferecem resolução suficiente para cumprir os requisitos de certas aplicações. Por conseguinte, é aqui proposta a concepção de um sistema capaz de localizar um módulo móvel em ambientes interiores com uma resolução de alguns centímetros. O conceito do sistema é baseado na medição da diferença dos tempos de chegada entre um sinal de radiofrequência e um sinal de ultra-sons de forma a calcular distâncias. A enorme diferença entre as velocidades de propagação das ondas RF comparativamente às ondas sonoras permitem ao sistema medir com precisão a diferença entre o tempo de chegada dos dois sinais e usar esse valor para estimar a distância que separa a fonte do destino.

Este documento descreve o desenvolvimento de todo o *hardware* necessário para a concepção de um protótipo bem como todos os aspectos relativos à implementação de *software*. Este sistema é composto por dois tipos de dispositivos que podem ser divididos em transmissores e receptores de sinais ultrassónicos. Cada dispositivo está equipado com um módulo de radiofrequência que lhes permite comunicar através de uma rede sem fios baseada no protocolo IEEE802.15.4. No final, foi alcançado um protótipo funcional que posteriormente foi submetido a vários testes de forma a avaliar o seu desempenho. Estes testes vieram corroborar a viabilidade deste método de localização com o protótipo a atingir um notável nível de precisão.

keywords

Real-time Locating System (RTLS), Indoor Positioning System (IPS), Time Difference of Arrival (TDOA), Tracking, Ultrasounds, Radio-Frequency, IEEE802.15.4, Wireless Communication, Microcontroller, Trilateration.

abstract

The increasing demand for tracking solutions in indoor environments has led to the development of many indoor location systems based in the most diverse technologies. They are trying to fill a market niche left by the current available location systems such as the well-known Global Positioning System (GPS). These systems are limited to an outdoor usage due to the drastic attenuation of the GPS signals in closed areas and they cannot provide enough resolution to meet the requirements of certain applications. Therefore, it's here proposed the conception of a system capable of locating a mobile module in indoor environments with an accuracy of a few centimeters. The system's concept is based in measuring the time difference of arrival (TDOA) between a radio frequency signal and an ultrasonic burst in order to measure distances. The huge difference between the propagation velocities of RF waves comparatively to sound waves allows the system to accurately measure the time difference between the two arrivals and use that value to estimate the distance that separates the source from the destination.

This document describes the development of all the necessary hardware for the conception of a final prototype and all the aspects regarding the software implementation. This system is composed by two types of devices that can be divided in Ultrasonic (US) transmitters and receivers. Each device is equipped with a RF module that allows them to communicate through a wireless network based in the IEEE802.15.4 protocol. In the end, a functional prototype was achieved that was subsequently submitted to several tests in order to evaluate its performance. These tests corroborated the viability of this localization method with the prototype achieving a remarkable precision level.

Table of Contents

1.	Introduction	1
1.1	Motivation.....	1
1.2	Overview, Proposition.....	2
1.3	Document Outline.....	3
2.	State of Art	5
2.1	Cricket system	6
2.2	Active Bat system	6
2.3	Dolphin system.....	7
2.4	ORL system.....	9
2.5	Parrot system	9
2.6	Comparison between systems	10
3.	System Development	13
3.1	Global architecture.....	13
3.2	Hardware requirements.....	14
3.2.1	μMRFs board	15
3.2.2	Ultrasonic sensors	18
3.2.3	Ultrasonic Transmitter	20
3.2.4	Ultrasonic Receiver.....	22
3.2.5	Printed Circuit Boards design	25
3.2.6	Cost analysis	29
3.3	Principle of operation.....	30
3.3.1	Distance measurement algorithm.....	31
3.3.2	Communication structure	33
3.3.3	IEEE 802.15.4 transceiver startup time limitation.....	34
3.3.4	Error detection and handling	36
3.4	Software implementation	38
3.5	System implementation in a supermarket.....	40
4.	Results	43
4.1	Power consumptions.....	43

4.2	Directivity	44
4.3	Measurements in a clean environment	45
4.3.1	Measurements carried out between one transmitter and one receiver	46
4.3.2	Mathematical adjustment.....	48
4.3.3	Measurements for each pair of transceivers individually	51
4.3.4	Measurements for one transmitter and three receivers	54
4.4	Real case study	56
4.4.1	Measurements in a “real life” environment	56
4.4.2	Measurements in a corridor.....	58
5.	Conclusions and future work	61
5.1	Conclusions	61
5.2	Future work.....	62
6.	Bibliography	65

List of Figures

Figure 1 - The Dolphin System [9]	8
Figure 2 – Composition of the devices.....	13
Figure 3 - μ MRFs board [16]	15
Figure 4 - IEEE 802.15.4 radio transceiver module [20, 21].....	17
Figure 5 - Ultrasonic transceivers.....	18
Figure 6 - Beam pattern and directivity of the chosen ultrasonic transceiver [23]	19
Figure 7 - Circuit schematic of the ultrasonic transmitter	20
Figure 8 - HCF4060 function diagram	21
Figure 9 - US receiver block diagram	22
Figure 10 - Signal amplification and filtering stage.....	22
Figure 11 - Detection with Automatic Gain Control	24
Figure 12 - Decision Stage	25
Figure 13 - Ultrasonic transmitter PCB layout (Top and Bottom).....	26
Figure 14 - Ultrasonic transmitter PCB layout	26
Figure 15 - US receiver PCB layout (Eagle design, Top and Bottom)	27
Figure 16 - Picture of the transmitter	28
Figure 17 - Picture of one receiver.....	28
Figure 18 - Transmitter block diagram.....	30
Figure 19 - Receiver block diagram	30
Figure 20 - Single measurement diagram	31
Figure 21 - Sending and Receiving RF signals (Measurements using an Oscilloscope)	34
Figure 22 - System explanation diagram for 30 measurements	35
Figure 23 - Tracking the transmitter using Trilateration techniques	35
Figure 24 - Flowchart describing the system's operation	37
Figure 25 - Receivers arrangement inside a supermarket [25].....	41
Figure 26 - Transmitter's directivity sketch.....	45
Figure 27 - Terminal of the receiver 1 after a measurement	54
Figure 28 - System appearance.....	55
Figure 29 – Arrangement of the fixed receivers	55
Figure 30 - Mediateca testbed	57
Figure 31 - Corridor measurements arrangement.....	58

List of Tables

Table 1 - Comparison between different indoor location systems [13]	10
Table 2 - Wireless technologies comparison [14]	14
Table 3 - Peripherals characteristics [17]	16
Table 4 - Microcontroller characteristics [19]	17
Table 5 - Comparison between the two ultrasonic transceivers [22, 23]	18
Table 6 - Transmitter's part list and respective cost	29
Table 7 - Receiver's part list and respective cost	29
Table 8 - Power consumptions of the US transmitter	43
Table 9 - Power consumptions of the US Receiver	44
Table 10 - Power consumptions of the μ MRFs module	44
Table 11 - Combined power consumption for a supply voltage of 12V	44
Table 12 - Measurements obtained for a supply voltage of 12V	46
Table 13 - Measurements obtained for a supply voltage of 17.5V	47
Table 14 - Comparison of the measurements and errors after adjustment	49
Table 15 - Measurements for the pair 1	51
Table 16 - Measurements for the pair 1 and 2	52
Table 17 - Measurements for three receivers	56
Table 18 - Measurements in Mediateca (*No line-of-sight)	57
Table 19 - Measurements in a corridor	59

List of Charts

Chart 1 - Transmitter in different supply voltages comparison	47
Chart 2 - Linear regression	48
Chart 3 - Comparison after adjustment	50
Chart 4 - Comparison of the deviation before and after adjustment	50
Chart 5 - Comparison between the three pairs	53
Chart 6 - Measurements carried out in a corridor	59

List of Acronyms

AC	Alternating Current
DC	Direct Current
RF	Radio Frequency
US	Ultrasonic
LoS	Line-of-Sight
TOA	Time of Arrival
TDOA	Time Difference of Arrival
RTLS	Real-time Locating System
IPS	Indoor Positioning System
LPS	Local Positioning System
GPS	Global Positioning System
IC	Integrated Circuit
DIP	Dual In-line Package
SMT	Surface-mount Technology
SMD	Surface-mount Device
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
SPI	Serial Peripheral Interface
TDMA	Time Division Multiple Access
ACK	Acknowledge
USB	Universal Serial Bus
ADC	Analog-to-Digital Converter
OPAMP	Operational Amplifier

1. Introduction

1.1 Motivation

Nowadays, the use of location information and its potentiality in the development of ambient intelligence applications has led to the design of many local positioning systems (LPS) based on different technologies. All of them involve gathering data by sensing a real-world physical quantity and using it to calculate or infer a position estimate. Research and development of real-time location systems (RTLS) started decades before, mainly targeting military and civilian needs for navigation and tracking. This resulted in the development of the well-known high tech Global Positioning System (GPS). Unfortunately, this system is limited to an outdoor usage due to the drastic attenuation of GPS signals indoors, the lack of line-of-sight and the low resolution that it can provide. Thus, location systems are mainly directed for outdoor environments, typically with a resolution of a few meters. Such precision is unacceptable for applications with higher accuracy requirements which has open the path to the research and development of real time indoor location systems (RTLS), mainly in the last decade.

This dissertation intends to develop a new location system devoted to an indoor use that can accurately estimate the position of a certain object. The applications of this system are innumerable but for now, it is mainly focused on tracking shopping carts inside a supermarket. In the end it is intended to be able to track their movements and provide to the supermarket's owner statistical information or other types of data that can be considered relevant. In fact, there's a big market demand for this particular application that will allow the large retailers to better understand the people's behavior inside their establishments, or in other words, the way they move along, where do they spend more time, etc. This system was designed in order to be low-cost, to have low-power consumption and reduced dimensions so it can be an attractive investment for potential buyers.

1.2 Overview, Proposition

It is hereby proposed the development of a real-time tracking system. This system should allow the user to locate anything inside a closed perimeter as long as that thing is equipped with one of our modules. This system is based on a hybrid technology combining the use of ultrasonic and radiofrequency signals which result in a system capable of delivering the highest location precision and reliability among all other technologies for an indoor use.

Besides the low cost of the transducers, the desirable properties that made the use of ultrasound an obvious choice consist of the known propagation velocity of sound waves in the air which is sufficiently slow to allow an extremely accurate measurement of its time-of-flight. Also, the inability of these signals of penetrating obstacles can work in the system's advantage since this way, they can be easily restricted to a limited area.

This real time locating system (RTLS) takes advantage of the huge difference between the propagation speeds of RF and ultrasonic (US) waves in order to calculate distances through the time difference of arrival (TDOA) method. The negligible propagation delay of the RF signal allows one to use this signal to synchronize the start of the transmission of an ultrasonic signal which will be posteriorly detected by a US receiver that will be able to determine its time-of-flight relatively to the reception of the RF frame. Thus, achieving extremely accurate distance estimations (inferred from the ultrasonic time of flight) becomes possible and that is the main ingredient for a fine-grained tracking solution.

The decision of choosing the general standard IEEE 802.15.4 aimed to minimize the general cost of this system and its power consumption levels which will define the autonomy of our mobile devices. The location is carried out by the following steps: A mobile module triggers a RF frame simultaneously with and an ultrasound burst that will reach a fixed receiver at different times. Usually the fixed receivers are mounted in a high ground position where the probability for a clear line-of-sight (LoS) is higher. The receiver will create a timestamp upon the RF signal receipt and measure the time difference among the two arrivals. After knowing this time difference, the fixed module is able to estimate the corresponding distance from the fixed module with a high accuracy, i.e., a maximum deviation of a few centimeters. It then sends that information to a server that will be responsible of combining three (or more) different distances from the same number of fixed reference modules so as to calculate the hyperbolic curves on which the mobile device is located and posteriorly compute its final localization. This conventional trilateration method is nowadays widely used in 3D location systems like, for example, the standard GPS. Another point in favor of this type of systems is that no clock synchronization between the stationary and the mobile modules is required to measure the time difference of arrival between both signals.

Nevertheless, if the goal is to achieve a proper real-time location, the fixed modules have to be able to generate precise timestamps and the clocks of the reference access points must be synchronized with each other in order to associate the obtained distances to a certain time instant.

Many obstructions such as walls, furniture or even people can lead to wrong measurements which will jeopardize the quality of the estimated location. Systems that use technologies that do not go through obstacles, such as the ultrasound, tend to be more accurate in indoor environments because only devices that have line-of-sight can communicate. However, that can generate other problems such as signal reflections, overlaps and multipath effects that have to be taken in consideration.

1.3 Document Outline

The document outline is organized in the following way:

- [Chapter 2](#): This document starts with an initial approach of the most relevant existing indoor location systems that are currently trying to find their market space giving a general overview of their operation and analyzing the main differences between them.
- [Chapter 3](#): Here is described the development of the system from scratch. First some considerations about the requirements are discussed and all the technologic choices are justified. Later in this chapter it's given a detailed explanation about all the designed hardware as well as all the aspects related to the proposed solution and the software implementation.
- [Chapter 4](#): Presents the achieved results and gives some considerations about all the tests that were performed with the system.
- [Chapter 5](#): Presents the conclusions resulting from this work and the future work that aims to the continuity of this project so that it can be improved and finished.

2. State of Art

Wireless technologies are widely present in our today's lives. Every modern location system that is not based on video processing resorts to this technology due to their high mobility that brings obvious advantages regarding implementation and maintenance aspects. As previously mentioned, the current outdoor location technologies such as the GPS have poor indoor performances and so they don't fulfill the requirements of typical indoor applications. Thus, indoor location systems are designed in order to provide higher accuracy and a more detailed location data that can include information about the physical space, position and orientation.

Many of the systems used nowadays are based in a signal's strength measurement because it decreases proportionally with the distance but this method is only suitable when there's no obstacles that will drastically change the power of the signal and cause reflections leading to erroneous readings. Apart from this method there is other solutions that are now starting to be commercialized. One of the most promising technologies is the systems based on the time of arrival (TOA), i.e., the absolute time that the signal takes to travel from a sender to a receiver. By applying this technique a time-stamping of the outgoing and incoming data is normally required. In this group it's possible to emphasize the ones that use a hybrid combination of RF and ultrasonic signals for a more precise and error-free location through the measurement of the time difference of arrival (TDOA) between the two. They resort to the fact that RF waves travel nearly at the speed of light as opposed to sound waves that are 10^6 times slower. Therefore, they usually use the RF signal as a reference for the starting of the transmission of both signals. Determining the time of flight of the ultrasounds with the starting reference described before is enough to calculate the distance among the emitter and the receiver with high precision. Furthermore, the ultrasounds are provided with the appropriate characteristics for this type of localization. They are very suitable to be used in indoor environments when the propagation to annexed rooms is not desirable. In such cases, the fact that they don't penetrate through obstacles can be seen as a big advantage.

The design and deployment of a system for obtaining location and spatial information in an indoor environment is a challenging task for several reasons, including the preservation of user privacy, administration and management overheads, system's scalability and the harsh nature of indoor wireless channels. The degree of privacy offered by the system is an important deployment consideration since people often value their privacy highly. This chapter will present and describe the existing location techniques that are based in this concept of using the two technologies for obtaining precise locations.

2.1 Cricket system

Cricket [1, 2, 3 and 4] uses a combination of RF and US technologies to provide location information to attached host devices. Two types of devices are used in this system, beacons and listeners. The beacons are usually placed in high grounds, like the top of a wall or a ceiling and the listeners are attached to the object to be located. Each beacon periodically transmits its location information in an RF message. With each RF advertisement, the beacon transmits a concurrent ultrasonic pulse. The listeners receive these RF and US signals and correlate them to each other. Upon the receipt of the first few bits of the RF signal they start counting the time delay between both pulses. The system is now in conditions to estimate the distance separating the listener and the beacon. The distance information of three or more beacon is enough to compute their own locations. The listener runs algorithms that associate RF and ultrasound samples and pick the best correlation. Even in the presence of several competing beacon transmissions Cricket achieves a good precision and accuracy.

Cricket is the result of several design goals, including user privacy, decentralized administration, network heterogeneity, low cost and low power consumption. Rather than explicitly tracking the user's location, Cricket helps devices to learn where they are and lets them decide whom to advertise this information to. It does not rely on any centralized management or control and there is no explicit coordination between beacons. Thus, it is possible to be implemented in applications that must preserve the user's privacy. This active-beacon passive-listener architecture is scalable with respect to the number of users and it can provide information to devices regardless of their type of network connectivity.

This system's drawbacks are common to all hybrid systems of this sort. Radio Frequency signals can interfere with other devices (e.g. pacemakers) and the ultrasonic emission in the presence of obstacles may lead to reflections that can threaten the quality of the measurements.

2.2 Active Bat system

The Active Bat system [5, 6 and 7] is an indoor location system that uses an active mobile architecture. It consists in tracking small active devices (known as bats) using a collection of fixed nodes arranged on a grid. These bats are usually of small size and low power consumption. Their job is simply to answer a RF query signal by emitting a narrowband ultrasonic pulse. One property that the Active Bat system has in common with many other location systems is that it does not make any assumptions about the position of a bat prior to a query being made.

The Bat ultrasonic pulses are scheduled via a radio channel, which is also used by bats to notify the system of their presence (this is known as registration). They can trigger

up to 50 location updates per second per radio zone. The system adaptively schedules Bat updates and offers highly-mobile Bats an increased priority by scheduling them more often. The ultrasonic pulses are detected by ceiling-mounted receivers that are carefully surveyed and know their positions in the building to sub-centimeter accuracy. When a pulse is detected, they measure the time between its RF command and the ultrasonic pulse receipt which will be approximately equal to the time-of-flight of the ultrasonic signal. These values are then forwarded to a central computer which estimates the distance that separates the Bats from the receivers. If the pulse is detected by three or more receivers then the position of the bat is calculated through multilateration. The system processes the raw Bat updates and rejects incorrect ultrasound responses by using an algorithm which requires at least three receivers to agree on a triangulation. This system can be very accurate. In fact, it doesn't exceed the 15 cm of error in 95% of the times. This system is designed to locate tags inside a room to a high degree of accuracy but is susceptible to multipath effects and reflections arriving at the receivers.

This system employs a centralized architecture in which both mobile transmissions and mobile position estimations are handled by a central computer. The biggest disadvantage of this system lies in the need of a monitoring station which makes the system centralized and so it does not preserve the privacy of the users. Apart from this privacy matter, the Active Bat system provides higher update rates, lower latency and greater levels of accuracy than are likely to be found in any deployed commercial indoor location system in the near future.

2.3 Dolphin system

The Dolphin system [8, 9] was designed to deal with the previous problems encountered on the BAT and Cricket systems. Unlike them, the DOLPHIN system requires only a few pre-configured reference nodes for locating all the other nodes in the system. The modules are pre-configured individually so they can work without interferences in a large-scale implementation.

The Dolphin is composed of several wireless sensors scattered by the location area that are able to transmit both US and RF pulses and have one-chip CPU that enables two of the elements to find the distance between them without resorting to an infrastructure. Despite this, some receivers must have a fixed position known by all the remaining elements because that is crucial for the proper functioning of the system.

The RF function is used for time synchronization and message exchange among nodes. The CPU has a pulse counter that is used to measure the TDOA of the ultrasonic pulse.

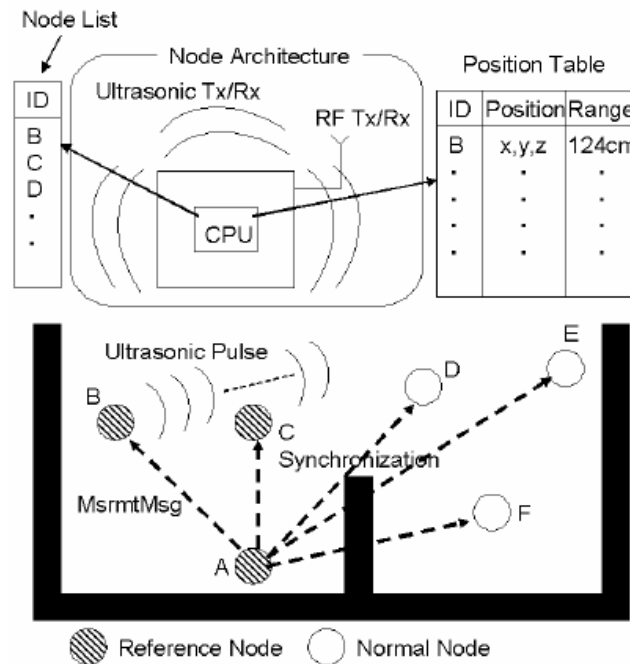


Figure 1 - The Dolphin System [9]

To better understand its functioning let's suppose that the reference node A in figure 1 transmits a query RF signal and an US pulse simultaneously. When the RF signal reaches all the other nodes, they start an internal pulse counter that is interrupted upon the arrival of the ultrasonic pulse. The RF signal contains the predetermined position of the node. They are then able to compute their distances to the node A based on the speed of sound using the TDOA measured value.

If the node collects 3 or more entries containing the distance information from nodes which positions have already been determined, it can compute its 3D position using a trilateration algorithm.

Since nodes are autonomous, there's not the need of a clear line-of-sight between all of them which means that this system can be accurate even in the presence of obstacles. For example, in figure 1, node D can determine its position using the reference nodes A, B, and C. However, node E and F are hidden behind obstacles and so they cannot receive all the ultrasonic pulses from the reference nodes. In this case, if the position of node D is determined and node E receives an ultrasonic pulse from node D, then node E can compute its position by using the known distances from node B, C and D. If the location of node D and E is determined, node F can compute its position using node C, D and E and so on. This makes possible the location of all nodes in the DOLPHIN system. That's clearly a huge advantage when comparing the DOLPHIN system with other indoor location systems. Another advantage of this system lies in the avoidance of signal interferences which makes it suitable for a large-scale implementation. This is made by using time-division multiplexing for the channel access. Despite being more adequate for a large-scale implementation,

Dolphin still lacks in user's privacy issues and it's still a centralized system due to the necessity of having elements with a fixed position.

2.4 ORL system

Following the concept used by the previously mentioned indoor location systems, the ORL system [10, 11] measurements are made from the time-of-flight of sound pulses that travel from an ultrasonic transmitter to receivers placed at known positions around it. The distance that separates a transmitter from a receiver can be calculated from the pulse transit times, from which, in turn, the transmitter's location will be found by multilateration.

The main difference of this system comparatively to the others lies in the hardware that is by far more complex. The object that is intended to be located is attached with a small wireless transmitter composed by a microprocessor, a radio transceiver, a FPGA (Field-Programmable Gate Array) and a hemispherical array of five ultrasonic transducers. Each device as a unique 16 bits address and it's powered by batteries.

The receivers are placed in a high ground position forming an array. They consist in an ultrasonic detector, whose output is passed through an amplifier, a rectifier and smoothing filter before being digitized by an analog-to-digital converter (ADC). The ADC is controlled by a Xilinx FPGA, which can monitor the digitized signal levels.

The receivers are connected to a control station through a serial network interface and can be individually addressable. Every time that a query RF signal it's sent, the control station orders the receivers to reset.

This system is proved to be very reliable in office environments. The information provided by the system is sufficiently fine-grained to allow investigation of a new set of context-aware applications. Furthermore, the wireless and low-powered nature of the location sensors allows them to be integrated into an everyday working environment with relative ease. Apart from this, the complexity, high cost and the need of specific hardware makes this system unprofitable and inadequate for the market's needs.

2.5 Parrot system

The Parrot system [12] uses the same technology combination of the other systems previously referred but provides a platform for an outdoor implementation. It's a GPS system competitor that is focused on getting where the normal GPS system can't guarantee

a precise operation. This system is composed by nodes, each node is equipped with a microcontroller, a RF transceiver and four pairs of ultrasonic sensors that can both send and receive. Periodically and in their respective time, a node sends out a RF pulse followed by an US burst which will allow the receiver node to estimate the distance between them through the TDOA method as explained before. The main difference that distinguishes this system is that not only it can determine the distance but also the orientation of the nodes.

The system consists of an internal wireless network by which the information about their relative positioning is shared. Every node makes part of that network and communicates through it. When the system starts, all active nodes are organized in an ordered list that is defined by the permission assigned to each node. This way, nodes know when to transmit and if any failure occurs they are removed of the list so that the system remains operational. It's true that there's not the necessity of having a single node controlling all the information flux but despite that, the system is still propitious to intrusions because any node has access to the information containing the position of all nodes. Another disadvantage of this system is that reflections can lead to erroneous readings especially if the US detection is made using four US sensors. The reason behind this choice must rest on the large increase in the system's accuracy which is claimed to be around 2 centimeters, the highest of all the described systems.

2.6 Comparison between systems

Here is a table that summarizes the main characteristics of the five location systems presented earlier:

System	Technology	Precision	Privacy	Decentralized	Cost
BAT	RF & US	3-14 cm	No	No	Low
Dolphin	RF & US	15 cm	No	Yes	Low
Cricket	RF & US	1.2 x 1.2 m	Yes	Yes	Low
ORL	RF & US	-	No	Yes	High
Parrot	RF & US	2 cm	No	Yes	Low

Table 1 - Comparison between different indoor location systems [13]

After studying these systems it's reasonable to conclude that the choice for the most appropriate one depends on the intended application. For typical implementations,

the ORL system is the first one to exclude. When considering its high cost and complexity, the ORL systems will be, in most cases, impracticable, unprofitable and inadequate.

If privacy issues are key, Cricket will undoubtedly be the option to take. It's the only system capable of ensuring the preservation of user's privacy. When this matter is not crucial we are left with three other systems that can give us a more precise localization.

The BAT system is simpler and allegedly a little more accurate than the Dolphin system but despite this, when comparing both systems, Dolphin seems to be a smarter solution with a huge advantage in the presence of obstacles. In this scenario, Dolphin would, in some cases, be able to locate all nodes present on the system even if they are "hidden" from the reference nodes which wouldn't be possible with the other systems. This is due to the fact that nodes are autonomous and able to communicate with each other. If a node has a clear line-of-sight with three or more different nodes (that may be or not referenced nodes), it will be able to compute its location in relation with them and so on until obtaining its final location. Additional references can be used to achieve a higher location accuracy and have an extraordinary impact in "non-clean" environments. Despite this, the practicality, low cost and simplicity offered by the BAT system in terms of implementation and maintenance makes it one of the most used systems in these days.

3. System Development

This chapter describes the development of the system from scratch. The discussion starts by giving a general insight of the architecture and concept of the system. An introduction follows in which some considerations about the hardware requirements are given together with an explanation of all the technological choices based on their characteristics and benefits regarding their application in the system's structure. Later in this chapter is given a detailed explanation about the electronic that had to be specially developed for this project as well as all the aspects related to the proposed solution including the system's operating principle, network topology, communication protocols and software implementation.

3.1 Global architecture

The first step is to get a general overview of the system's concept. The idea is to have an infrastructure capable of gathering and providing information about the location of mobile devices within a closed perimeter. All devices forming part of the system must communicate in a Master/Slave configuration via radiofrequency. The infrastructure is composed by a master US receiver that is responsible for triggering the location request and by two US receivers in a slave configuration. The data gathered by the two slaves is routed to the master where all calculations are performed. Thus, all data processing is performed in the infrastructure side. The mobile devices are also configured as slaves and so they are completely autonomous when responding to a location request given by the infrastructure. They must run on batteries and incorporate an omnidirectional US transmitter and a RF module for distance measurements and communication. In Figure 2 is presented the composition of these devices in a simplified way.

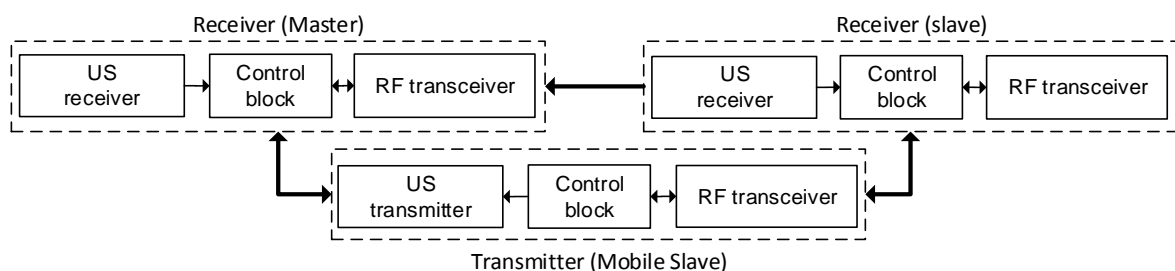


Figure 2 – Composition of the devices

3.2 Hardware requirements

The system is composed by two groups of devices that have to be able to communicate between them wirelessly. For that, they have to be equipped with wireless transceivers. There is different types of technologies that could be used for that purpose but attending to the following table and considering the application requirements is relatively easy to choose among the available and most common communication protocols.

Communication Protocol	IEEE 802.15.4	Bluetooth (IEEE 802.15.1)	Wi-Fi (IEEE 802.11a/b/g)
Transmission rate	≤125 Kbit/s	723 Kbit/s	54 Mbit/s (Depending on the protocol);
Power consumption	Very low	Low	Medium
Range	10-100 m	10(50-100) m	50-100m

Table 2 - Wireless technologies comparison [14]

The power consumption is of extreme importance because it will determine the autonomy of the mobile devices. Also, the system doesn't require high transmission rates since only very short frames will be used for communication. For this reason, the protocol that best serves the purpose of the system is the IEEE 802.15.4.

Apart from communicating, these devices will use this wireless technology combined with ultrasonic bursts for measuring distances. At this point, it is possible to divide the devices in transmitters (mobile) and receivers (fixed) of US signals. Thus, a transmitter has to be able to emit ultrasonic bursts whenever necessary and the receiver has to be prepared to notify the detection of these signals. In order to make them user friendly, the wireless nodes need to be small, easy to install, preferably cheap and have low power consumptions for achieving a high autonomy while operating with batteries.

In this part, all the necessary hardware will be addressed from which is possible to emphasize the microcontroller that will be used to control all the involved peripherals, the RF module that will allow to establish communication between devices and the US transmitter/receiver that were specifically designed for this system. The microcontroller and the RF transceiver that were used in this system are integrated in the μ MRFs module that is described in the next section.

3.2.1 μ MRFs board

The μ MRFs module was developed and provided by Micro I/O [15] and offers a variety of useful features for embedded solutions in wireless applications. It incorporates, among other things, a 2.4GHz IEEE 802.15.4 transceiver module, an accelerometer, a temperature sensor, a battery connector and a PIC18F26K20 with all the necessary hardware allowing USB connectivity through a USB-UART converter. The main purpose of this board is to enable an easy to use wireless communication following the standard protocol IEEE 802.15.4. The PIC18F is used to control all the peripherals which will also include the ultrasonic receiver/transmitter that were created for this project's purpose and will be connected by the extension pins already existing in the board. Therefore, it allow to control the RF transceiver together with the attached Ultrasonic transmitter/receiver which combined with the already existing resources will fill all the hardware demands in order to start gathering and processing all the necessary data to reach a final localization.

Peripherals and specifications

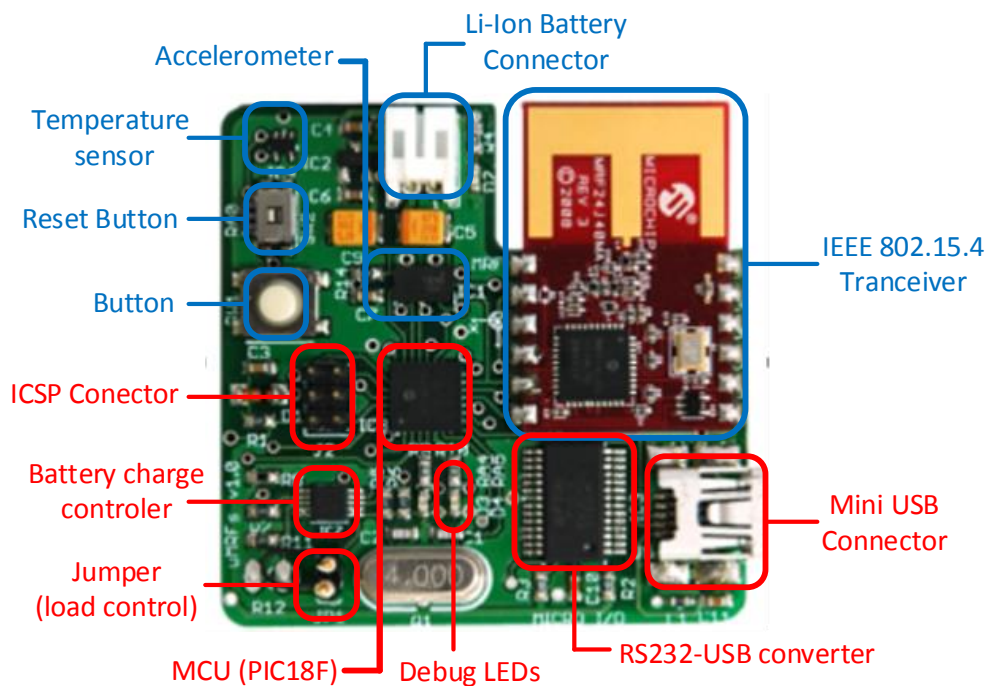


Figure 3 - μ MRFs board [16]

The following table contains some information about the peripherals and the main components included in μ MRFs module [16]:

Peripherals		
Description	Model and Manufacturer	Characteristics
Digital accelerometer	MMA7455L by Freescale	Current consumption: 400uA Selectable Sensitivity: $\pm 2g/4/8$ for 8-bit mode
Temperature sensor	MCP9700 by Microchip	Accuracy: 4°C Low Operating Current: 6 μ A Analog Output
Charge management controller	MCP73833 by Microchip	Vcc Range: 3.75V to 6V Voltage Regulation Accuracy: 0.8%
USB-series converter	FT232R by FTDI	USB to UART Supply voltage range: 1.8V to 5.25V
Microcontroller	PIC18F26K20 by Microchip	8-bit nano watt XLP technology Up to 16 MIPS
IEEE 802.15.4 Radio transceiver	MRF24J40MA by Microchip	Frequency: 2.4 GHz Data rate: 250kbps Range: up to 400m

Table 3 - Peripherals characteristics [17]

Microcontroller PIC18F26K20

The PIC18F26K20 [18] is a microcontroller from the PIC18F product family manufactured by Microchip. It has an 8-bit CPU and it's an upgrade over the oldest PIC16F device family offering better performances with operating speeds up to 16 Million Instructions Per Second (MIPS) and has a hardware multiplier for faster calculation of control algorithms. Recently, Microchip started developing eXtreme Low Power (XLP) microcontrollers with a technology that they called nanoWatt XLP technology [18] due to the increasing importance of energy conservation in electronic applications. It's claimed to be the industry's lowest power, widest operating voltage range, and most flexible power-managed technology available for embedded systems today. Thus, products with this technology offer the market's lowest currents for Run and Sleep, where low power applications spend most (>90%) of their time. This feature becomes very important in this type of applications where usually a battery powered device must run several years with a single charge.

The main characteristics of the PIC18F26K20 are presented in the next table:

PIC18F26K20 Microcontroller		
Type	8-bit nano Watt XLP Technology	
Frequency	Up to 64 MHz (internal oscillator)	
Program Memory	Flash (bytes)	64k
	# Single-Word Instructions	32768
Data Memory	SRAM (bytes)	3936
	EEPROM (bytes)	1024
Analog to digital converter		10 bit - 11 channels
Input/output Pins		25
Communication interfaces		EUSART, SPI, I ² C™
Timers		1x8-bit, 3x16-bit
Internal comparators		2
Others		1xCCP, 1xECCP (PWM)

Table 4 - Microcontroller characteristics [19]

IEEE 802.15.4 radio transceiver module



Figure 4 - IEEE 802.15.4 radio transceiver module [20, 21]

The MRF24J40MA [20, 21] is a certified 2.4 GHz IEEE 802.15.4 radio transceiver module developed by Microchip. The MRF24J40MA has an integrated PCB antenna, matching circuitry and supports the ZigBee™, MiWi™ and MiWi P2P protocols with a data rate up to 250kbps. The MRF24J40MA module is connected to the PIC18F microcontroller in a master/slave configuration via a 4-wire serial peripheral interface (SPI) bus which is a synchronous serial data link that can operate in a full duplex mode. Thereby, they can communicate simultaneously in both directions through four logic signals (SCLK, MOSI, MISO and SS).

This module is a good solution for wireless sensor networks, home automation, building automation and consumer applications due to its high range (up to 400meters), low cost and low current consumption (Tx 23mA, Rx 19mA, Sleep 2uA).

3.2.2 Ultrasonic sensors

Ultrasonic sensors are commonly used for a wide variety of non-contact presence, proximity or distance measuring applications. An ultrasonic transducer is a device that converts electrical energy into high frequency sound waves that are outside the normal hearing range of humans, typically between 40 kHz and 250 kHz. The large variety of sensors commercially available differ from one another in their mounting configurations, environmental sealing, and electronic features. The piezoelectric sensors generate sound waves by applying an alternating current (AC) across a piezoelectric crystal. These crystals have the property of changing size accordingly with the applied alternating current thus originating an oscillation at a very high frequency which results in the production of ultrasonic waves. This type of sensors is the most adequate for the concerned application.

The choice of the MA40B8R/S [22] piezoelectric ultrasonic sensor was based on its low cost and availability in the market. In fact, when this dissertation was started, they were the only option available that would fill our demands for an affordable price. Despite this, its low detectable range and directivity soon proved to be insufficient for the desired application. It was possible to detect US signals at the maximum range announced by its manufacturer, however, they were very susceptible to fail in detecting those signals after a slight deviation of a few degrees in its orientation. Later on, new ultrasonic transceivers were released. The MCUSD16A40S12RO [23] announced a detectable range four times higher than the previous sensors for half of the cost and so they become the obvious choice. Here are the specifications of both sensors:



Figure 5 - Ultrasonic transceivers

Sensor	MA40B8R/S	MCUSD16A40S12RO
Construction	Open structure type	Open structure type
Using Method	Different for Tx and Rx	Dual use
Nominal Frequency (kHz)	40	40
Output Sound Pressure (dB)	120 ± 3	110
Sensitivity (dB)	-63 ± 3	-65
Capacitance (pF)	2550 ± 20%	2500 ± 25%
Directivity (degrees)	80°	50°
Operating Temp. Range(°C)	-40 to 85	-35 to 85
Detectable Range (m)	0.2 to 4	0.7 to 18m
Resolution (mm)	9	Not specified
Allowable Input Voltage (Vpp) (Rectangular wave)	20	Not specified
Housing material	Plastic	Aluminum

Table 5 - Comparison between the two ultrasonic transceivers [22, 23]

Acoustically, both sensors operate at the same frequency but they have different radiation patterns. When working with this type of devices its essential to be aware of its characteristics. The main issue in this matter comes from their variable gain along the bandwidth. In addition to that, the ultrasonic transceivers have a slow start and feature a continuous oscillation after ending the transmission. It is also very important to take in consideration their directivity and beam patterns accordingly to the intended purpose. In figure 6 it's described the behavior of the MCUSD16A40S12RO over its bandwidth together with a representation of this sensor's directivity.

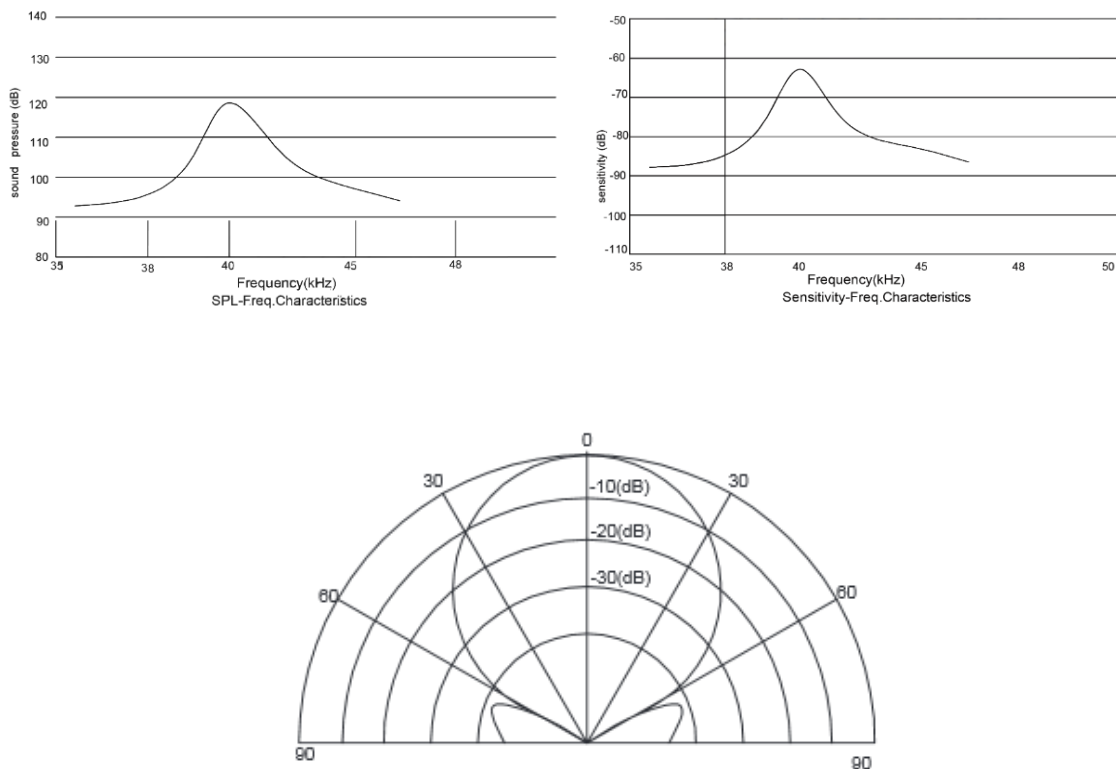


Figure 6 - Beam pattern and directivity of the chosen ultrasonic transceiver [23]

As expected, the directivity of this ultrasonic transceiver is somewhat limited presenting an attenuation of 10dBs for an angular misalignment of only 30 degrees. This will imply the use of, at least, six transceivers if the objective is to achieve an omnidirectional transmission and considering that this transceiver is still viable for an angular deviation of 30°. As positive aspects it's worth to stand out the high output sound pressure, the low power consumption and the high reliability of this sensor. This together with being compact and lightweight makes it perfect for applications like burglar alarms, automatic doors, remote control or range finders.

3.2.3 Ultrasonic Transmitter

The Ultrasonic transmitter was designed in order to communicate with the microcontroller by way of 2 pins: one is used to connect both grounds while the other one acts as an enable digital input that triggers the US transmission when is active. The transmitter has an independent power source (supplying 12V) which is needed to provide the sufficient peak to peak voltage to the sensor terminals. This transmitter can be divided in three different stages. In figure 7 it's presented the complete circuit schematic of the ultrasonic transmitter:

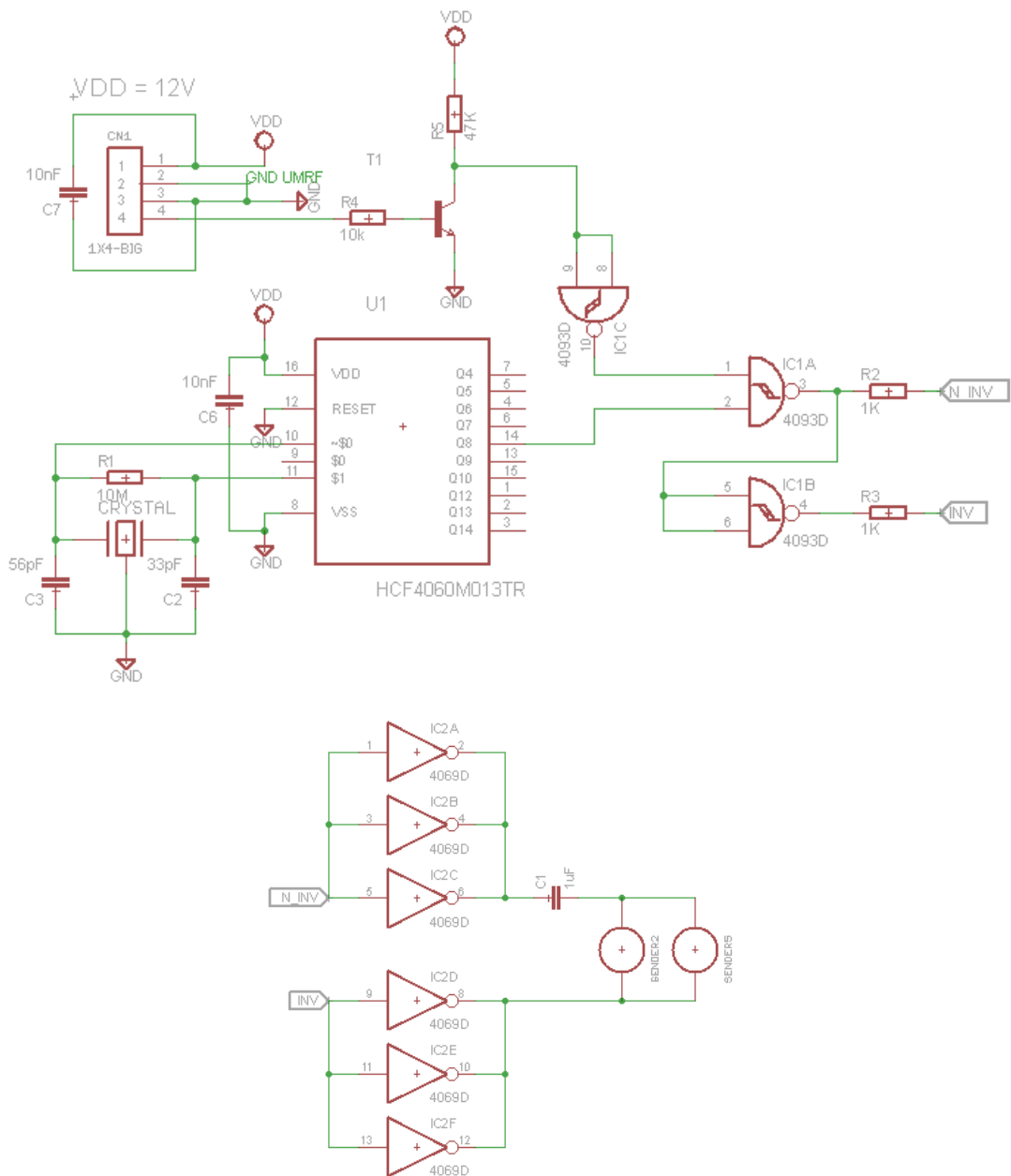


Figure 7 - Circuit schematic of the ultrasonic transmitter

The first stage was designed in order to obtain a rectangular wave with a nominal frequency of 40 kHz which is the carrier frequency that is used by this type of ultrasonic sensors and consists of a 10.24MHz crystal connected to a binary counter/divider. The HCF 4060 contains an easy to use astable followed by a 14-stage binary counter/divider which makes it perfect for this application.

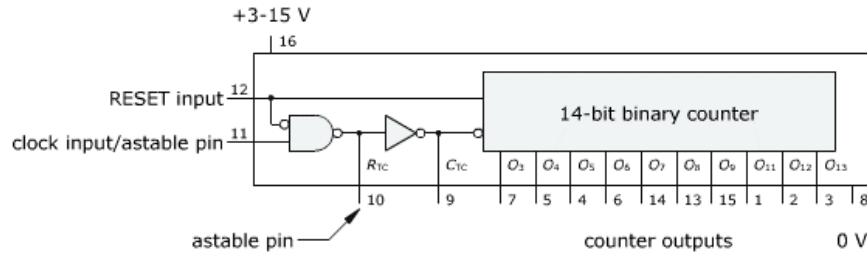


Figure 8 - HCF4060 function diagram

Pulses from the astable are passed to the binary counter/divider and so in the output pin O₃ the frequency of those pulses is divided by $2^4=16$ compared with the initial. Pulses at O₄ have half the frequency of pulses at O₃ and so on. With a crystal oscillating at 10.24MHz in its input one can easily obtain the desired frequency of 40 KHz in the output pin O₈ ($10.24 \text{ MHz}/2^8 = 40 \text{ KHz}$).

The second stage takes the signal resulting of the binary divider output and generates a second 180 degrees phase shifted signal using only NAND logic gates with Schmitt trigger inputs thus reducing the noise influence on the circuit. This is due to the necessity of having two rectangular waves with the same frequency but with opposite phases applied to the US pins as it doubles the voltage effectively (the rms voltage doubles from 6V to 12V) applied to the US transducer (when compared with the case of one of the pins grounded). This stage also incorporates the correlation of the enable input signal with the rest of the circuit. This signal (coming from the microcontroller) is firstly amplified with a simple bipolar junction transistor (BJT) in a common emitter configuration and then connected to one of the NANDs inputs in order to function as an enable for the rest of the circuit.

The final stage operates as a buffer and it's only composed by inverters. The inverter is used as a drive for the ultrasonic sensor. The three inverters are connected in parallel in order to supply all the necessary power for a long distance transmission. Taking that into consideration and in order to achieve an omnidirectional directivity with maximum range it was decided to place two ultrasonic sensors in parallel for each pair of inverters as represented in figure 7.

The capacitor C1 is used to eliminate the DC component of the signal thus protecting the US sensors from getting damaged.

3.2.4 Ultrasonic Receiver

The project of this receiver was made in three different stages. First comes the signal amplification and filtering circuit followed by a detection circuit with an automatic gain control (AGC) and finally the decision stage. These stages are represented on the block diagram of figure 9.

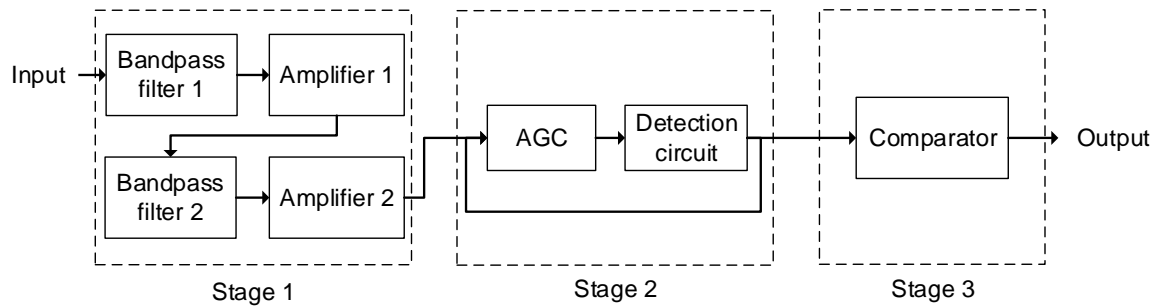


Figure 9 - US receiver block diagram

Signal amplification and filtering circuit

The circuit schematic correspondent to the first stage is presented below:

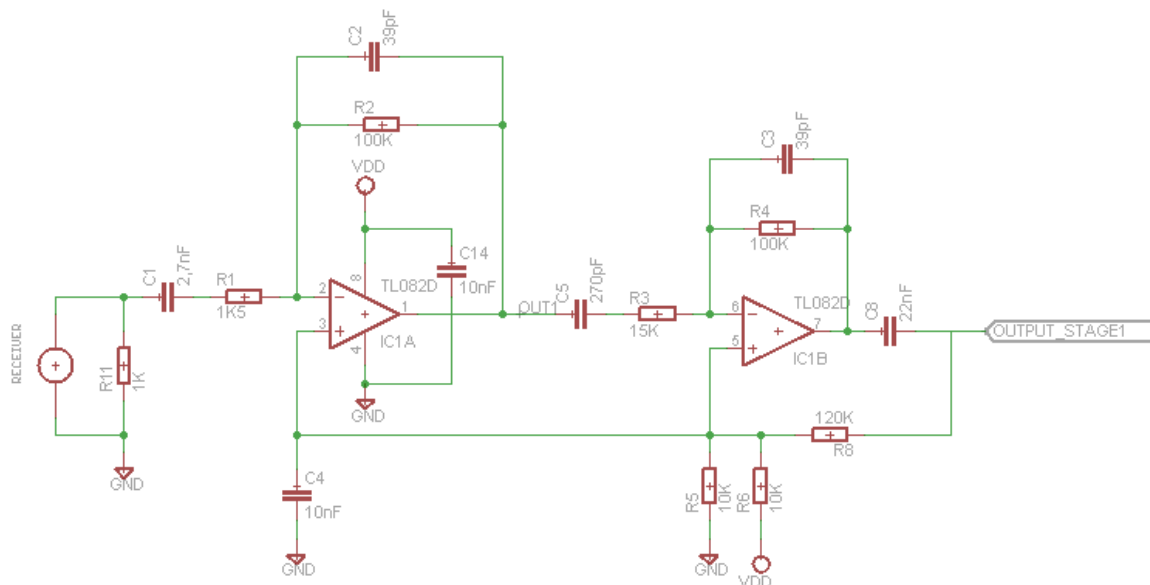


Figure 10 - Signal amplification and filtering stage

This stage is responsible for amplifying and filtering the signal picked by the ultrasonic transceiver. For this purpose, the obvious choice was to use a filter with a Bandpass characteristic which has the ability to pass frequencies relatively unattenuated over a specified band. For increasing the amplification and refine the center frequencies of the filter without compromising the quality of the signal it was decided to combine two band pass filters. The calculations for the filters project are presented below (according to the circuit of figure 10):

$$V_{gain1} = -\frac{R_2}{R_1} = -\frac{100K}{1K5} = -66.6 \approx 36.5 \text{ dB}$$

$$V_{gain2} = -\frac{R_4}{R_3} = -\frac{100K}{15K} = -6.6 \approx 16.4 \text{ dB}$$

$$V_{gain} = 66.6 * 6.6 = 444.444 \approx 53 \text{ dB}$$

$$f_{c11} = \frac{1}{2\pi R_1 C_1} \approx 39.3 \text{ KHz}$$

$$f_{c12} = \frac{1}{2\pi R_2 C_2} \approx 40.8 \text{ KHz}$$

$$f_{c21} = \frac{1}{2\pi R_3 C_3} \approx 39.3 \text{ KHz}$$

$$f_{c22} = \frac{1}{2\pi R_4 C_4} \approx 40.8 \text{ KHz}$$

Joining both filters the total gain is about 53 dBs over a 1.5 KHz bandwidth which is sufficiently narrow to reduce non desirable interferences. The need for such a high gain can be explained by the detectable signal in the receiver. For distances larger than a few meters the generated voltage at the sensor terminals is in the order of millivolts and so it has to be converted in workable values.

Generally, symmetrical voltages are applied to supply the operational amplifiers but this circuit works with a single power supply of 0 to +12V. A bias voltage of half of the power supply voltage is set in the positive input of the operational amplifier. This bias voltage comes from a resistive divider with two equal resistances (R5 and R6) connected between the supply voltages. Since there is negative feedback, the voltage of the positive input and the voltage of the negative input become approximately equal. Thus, is to be expected that both the positive and the negative part of the alternating current signal will be equally amplified.

Detection circuit with automatic gain control

This part of the receiver is responsible for the US signal detection and the automatic gain control (AGC) of the detected signal level. The detection is made resorting to a half-wave rectification circuit composed by two Schottky barrier diodes, a capacitor and a resistor. The schematic is presented in figure 11.

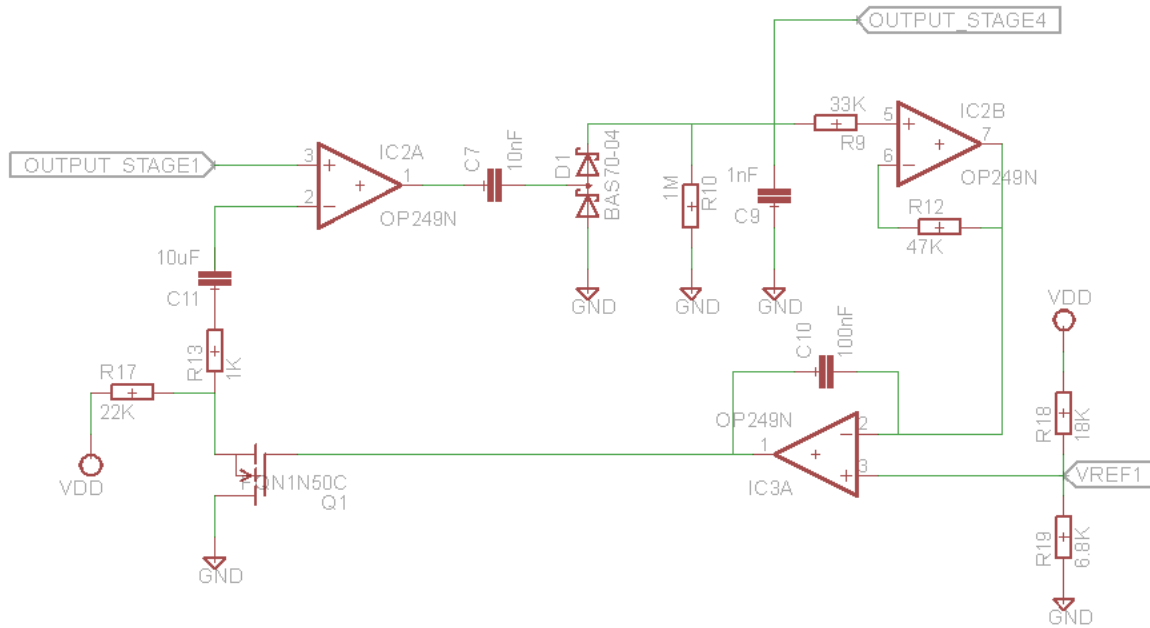


Figure 11 - Detection with Automatic Gain Control

Schottky diodes are used because they have a lower voltage drop when direct biased (their better high frequency characteristic is not relevant for US frequencies). The DC voltage is gotten by the capacitor behind the diode according to the level of the detected peak level of the signal. The averaged peak level is used to adjust the gain of the AGC to maintain a certain suitable level (set by VREF1) thus enabling the circuit to work satisfactorily with a larger range of input signal levels. Every time the output signal of the detection circuit goes below the reference voltage the integrating OPAMP output changes to high increasing the V_{GS} of the mosfet that consequently exits the cutoff region (no conduction between drain and source) to the saturation region (active mode, $I_D \neq 0$) which will increase the gain of the first amplifier setting the level of the detected signal back to the desirable one in a very fast response time. If the input signal becomes large, the integrating OPAMP output forces the gain to go in the opposite direction.

Decision stage

The final stage it's a simple comparator. It sets a digital output accordingly with the signal level found after the detection stage. This is made by comparison with a reference voltage level that is applied in the negative input of the operational amplifier (as comparator). Every time the output of the detection stage exceeds this value the output is set to HIGH (+12V) meaning that an ultrasonic signal was successfully received. Lastly, the output is connected to the μ MRFs board through a DC decoupling capacitor with the help of a connector plug.

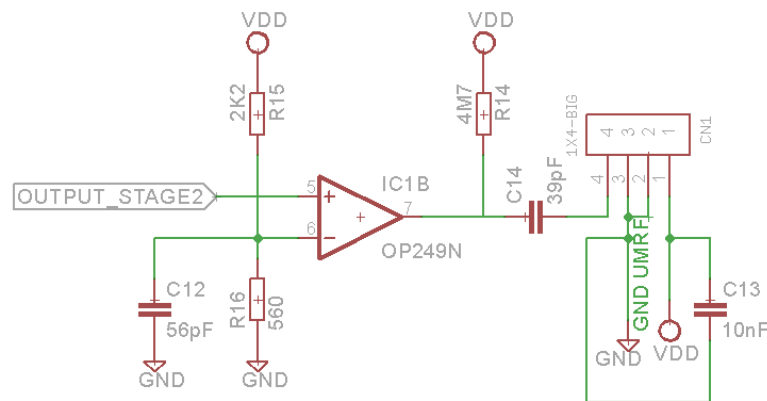


Figure 12 - Decision Stage

3.2.5 Printed Circuit Boards design

The schematics of the ultrasonic transmitter and receiver presented before were firstly tested in breadboards. After successfully achieving the desirable results it was time to start designing the layout of the printed circuit boards based on the functional schematics. This was done entirely using the Eagle CAD software [24] and attending to all the design rules that are required for in-house production. Therefore, the standard levels of clearance, isolation, distances, drill holes and the width of signal layers, pads and vias had to be adjusted accordingly. Only surface-mount devices (SMD) were used in order to make the boards as small as possible. The final layouts for both layers of copper are presented in the next pages.

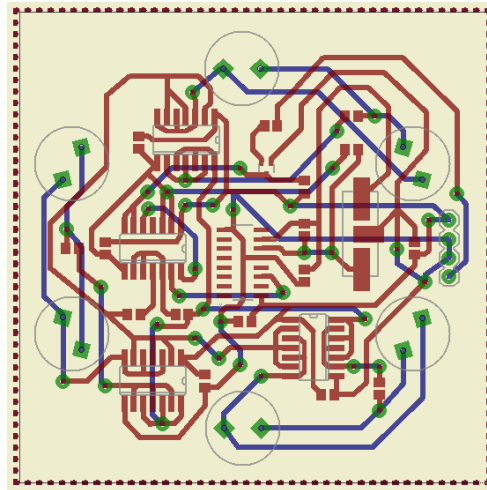


Figure 14 - Ultrasonic transmitter PCB layout

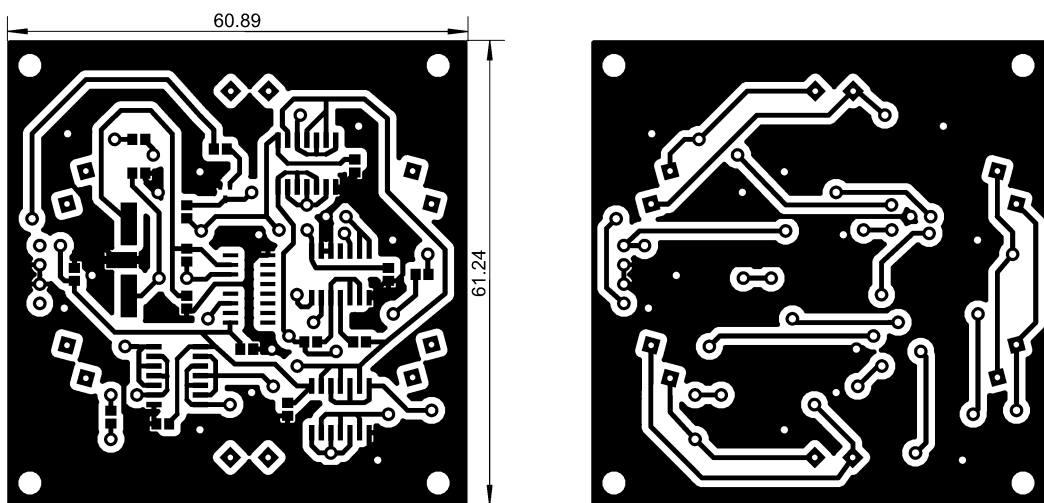


Figure 13 - Ultrasonic transmitter PCB layout (Top and Bottom)

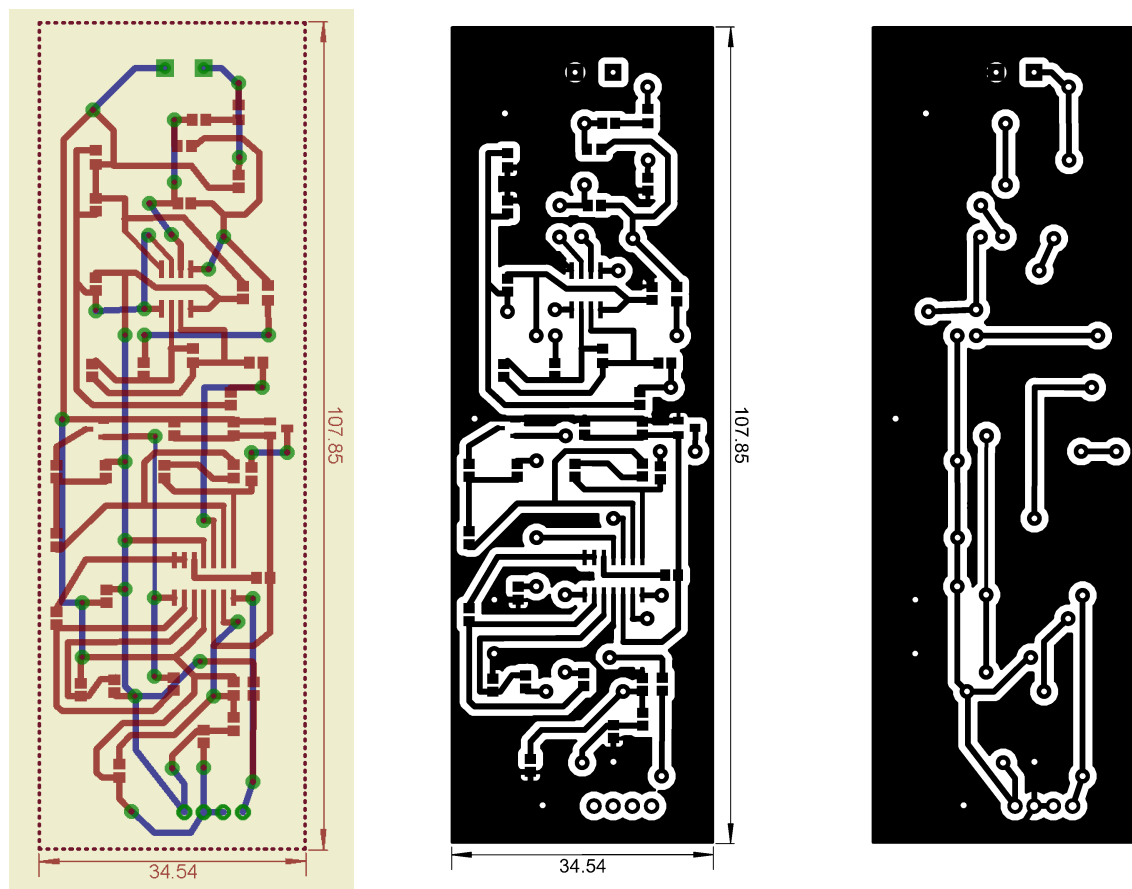


Figure 15 - US receiver PCB layout (Eagle design, Top and Bottom)

The printed circuit board was entirely made using the resources available in the University of Aveiro. All SMD components were manually welded with final appearance in figures 16 and 17.

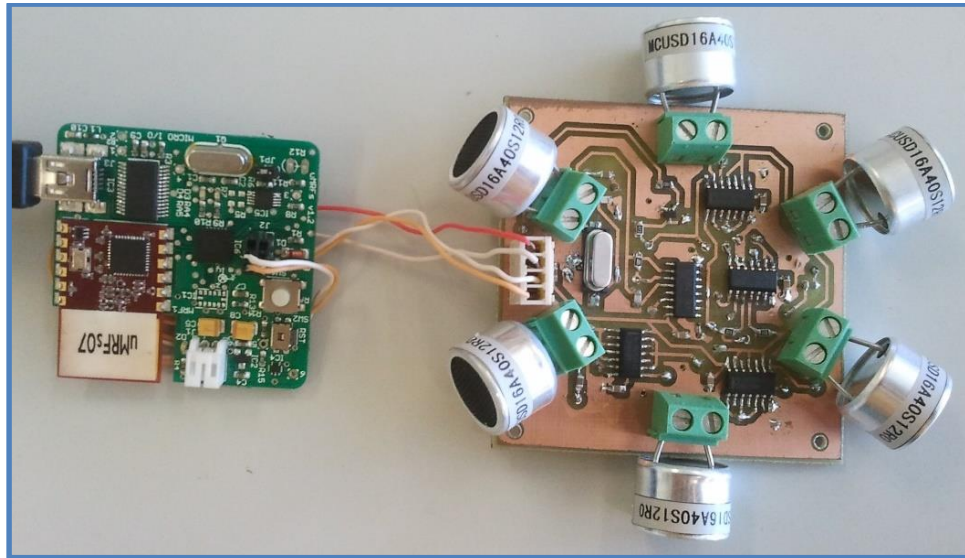


Figure 16 - Picture of the transmitter

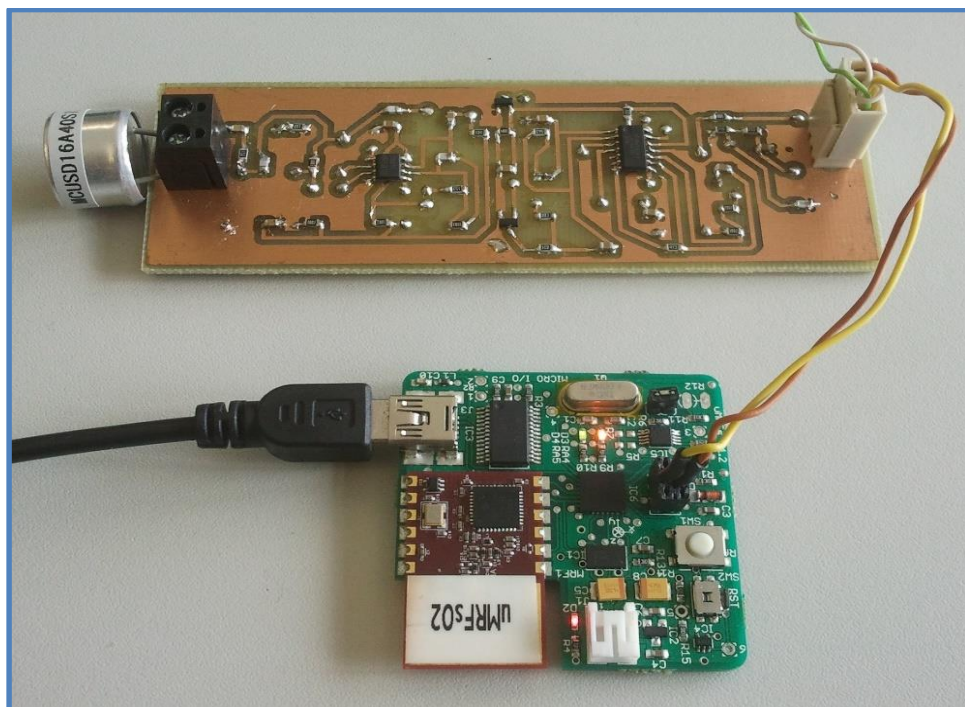


Figure 17 - Picture of one receiver

3.2.6 Cost analysis

Here is the components list for both of the boards with the correspondent current market cost. This way is possible to have an idea of their production costs which would certainly decrease in a large-scale implementation.

Transmitter	Quantity	List price	Total cost
US Transceiver	6	2,57 €	15,42 €
Crystal 10.24MHz	1	0,76 €	0,76 €
NANDS (HCF 4093)	1	0,46 €	0,46 €
Inverters (CD 4069)	3	0,42 €	1,26 €
Binary counter (HCF 4060)	1	0,55 €	0,55 €
Capacitors	11	≈ 0,05 €	0,55 €
Resistors	5	≈ 0,22 €	1,10 €
Connector + contacts	1	1,65 €	1,65 €
Total			21,75 €

Table 6 - Transmitter's part list and respective cost

Receiver	Quantity	List price	Total cost
US Transceiver	1	2,57 €	2,57 €
Diodes (BAS70-04)	1	0,55 €	0,55 €
Opamps (TL082ACD)	1	0,80 €	0,80 €
Opamps (LMC 6494BEM)	1	3,30 €	3,30 €
Mosfet (2N7002-7-F)	1	0,12 €	0,12 €
Capacitors	16	≈ 0,05 €	0,80 €
Resistors	19	≈ 0,22 €	4,18 €
Connector + contacts	1	1,65 €	1,65 €
Total			13,97 €

Table 7 - Receiver's part list and respective cost

Is fair to say that the cost of manufacturing these boards is mainly established by the price of US transceivers. The values used for capacitors and resistors were settled by the average prices of these components in online stores. The overall cost of these devices is low, and deploying it in a large scale could be a viable solution because it wouldn't represent a big investment.

3.3 Principle of operation

This indoor location system was designed aiming a future implementation inside a supermarket and so it has to be able to work in such environment that is mainly composed by corridors separated by tall shelves and people with shopping carts moving along them.

As previously stated, the system is composed by two types of devices, the transmitters and the receivers. Here are the block diagrams that represent their configuration:

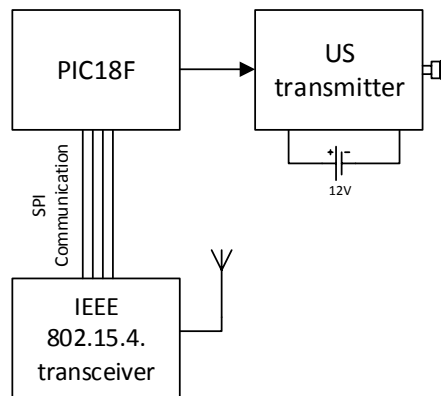


Figure 18 - Transmitter block diagram

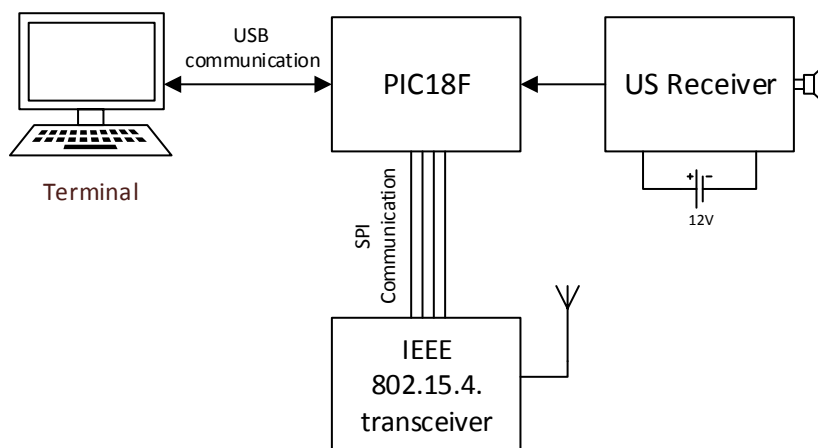


Figure 19 - Receiver block diagram

The transmitter is mobile, battery-powered and will be attached to the shopping carts which are intended to be located. It has all the necessary hardware to communicate following the IEEE 802.15.4 protocol and to control the transmission of US signals. Analogously, the receiver is equipped with the same RF module and a US receiver capable of detecting low power US signals at large distances.

The proposed solution is somewhat similar to the well-known GPS. The receivers will act as satellites that will be able to calculate the position in space and time of the mobile transmitter relatively to them in order to reach its current location. An unobstructed line-of-sight between the transmitter and three or more receivers is fundamental for the success of the localization. Therefore, ceiling mounted receivers are used to guarantee this condition in pre-determined fixed positions that will be used as references. This subject will be addressed further in this document, for now let's analyze the concept of the system and explain in detail the procedure for obtaining a single distance measurement.

3.3.1 Distance measurement algorithm

The system starts by measuring the distance that separates the transmitter of the receivers individually. This is done by resorting to the Time Difference of Arrival (TDOA) method which has the huge advantage of not requiring clocks synchronization between transmitters and receivers. This is because a RF signal is used to synchronize the transmission and reception of the US burst. The only elements that need to be synchronized are the receivers (part of the infrastructure) because of a correlation of three or more measured distances must be associated to the same time instant to achieve a real-time location. Here is a diagram that shows how a single measurement is processed:

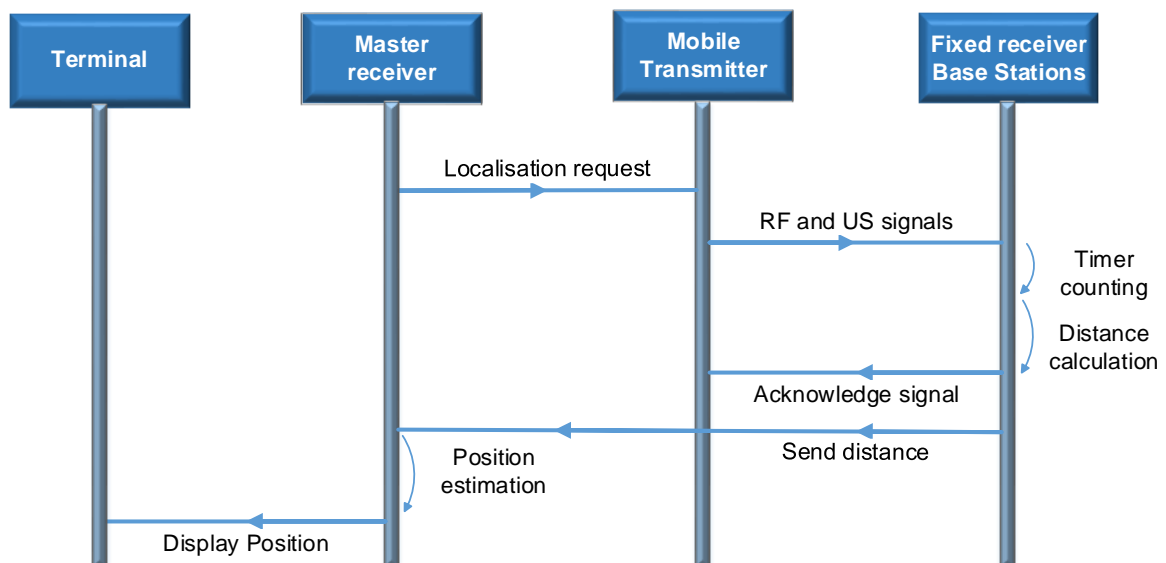


Figure 20 - Single measurement diagram

The location request can be done by the main server through a radio-frequency trigger signal or, in this case, by pressing a button on the μ MRFs board. Upon receipt of the location request the transmitter sends a RF burst simultaneously with an Ultrasonic signal and enters an idle state waiting for an RF acknowledge. Experimentally it was determined that the minimum duration so the ultrasonic burst can be successfully received is around 100 microseconds so the duration of the US signal was set to 2 milliseconds thus ensuring the highest range and not compromising our measurement time.

When the receiver listens to the RF signal it starts a timer (timer0 of the used microcontroller) that is stopped upon the US receipt. If the US burst does not come within a predefined time interval the timer will generate an interruption due to its overflow after 60 milliseconds that corresponds to a distance greater than 20 meters (for normal temperatures) which goes far beyond our maximum ultrasonic range. In practical terms we are measuring the time difference of arrival (TDOA) between both signals which will be approximately equal to the Time of Arrival (TOA) of the US signal since the RF propagation speed is practically instantaneous when comparing to the speed of sound. When this process finishes, the receiver sends out an ACK signal indicating the success of the measurement to the transmitter.

The obtained time can be easily converted into distance following a line of reasoning that starts with the calculation of the speed of sound correspondent to the current air temperature by the following expression where T_c is the temperature in Celsius:

$$V_{sound\ in\ air} = 331.4 + 0.6 \times T_c\ (m/s)$$

This equation describes the variation of the speed of sound in the air as a function of temperature. As it's easily perceptible, the speed of sound increases with the air temperature. This is because heat is a form of kinetic energy, its origin is in the vibration of the molecules which have more energy at higher temperatures. More energy corresponds to a faster vibration allowing sound waves to propagate at higher speeds. The speed of sound is also affected by other factors such as humidity and air pressure.

After calculating the speed of sound for the appropriate temperature, the estimated distance is obtained by simply multiplying it by the TDOA that was measured. To pass the TDOA value to real time units, first is necessary to convert the hexadecimal count value (read in the timer0 register) to a decimal number and then correlate it with the frequency accordingly with the timer configuration. The timer0 was configured as a 16-bit timer, with the internal instruction cycle clock (CLKOUT) as the clock source and with no prescaler assigned. In this case our PIC18F was operating at 4 MHz which means that the timer frequency will be $\frac{F_{osc}}{4} = 1\ MHz$ and so:

$$TDOA_{real\ time} = Time\ register \times \frac{1}{1 * 10^6}\ (s)$$

And finally:

$$\text{Estimated distance} = V_{\text{sound in air}} \times TDOA_{\text{real time}} (m)$$

Thus, to estimate one distance no clock synchronization is required. After getting the estimated distance, the first receiver informs the transmitter about the success of the measurement by sending him an ACK frame. The same process is repeated for the second and third receivers. After that is concluded, the real location of the transmitter can be computed by trilateration techniques using the receivers as reference points.

3.3.2 Communication structure

The communication between devices is crucial for the success of this system. In order to make this communication easier, all radiofrequency frames must obey a predefined structure that will inform the listeners about the purpose of the frames as well as their source and destination. A frame is a simple array of bytes with a length of 5 elements that is composed and organized in the following way:

Description	Start	Source address	Destination address	Distance value (optional)	Purpose
Index (Bytes)	0	1	2	3	4

- Start – indicates the start of the frame
- Source address – Contains the source address of the frame
- Destination address – Contains the destination address of the frame
- Distance value – This field is only valid for the exchange of distance values between receivers
- Purpose – It's used to distinguish frames. This field can contain a value from 0 to 2 depending on the purpose of the frame:

0	Burst used for measurements
1	Acknowledge indicating the success of one measurement
2	Field containing a distance value

3.3.3 IEEE 802.15.4 transceiver startup time limitation

The figure below shows the time interval between the RF trigger command and the correspondent signal reception for several transmissions. This print screen was taken with the oscilloscope in persistent mode and with the trigger configured for when a change from low to high is detected in channel 1:

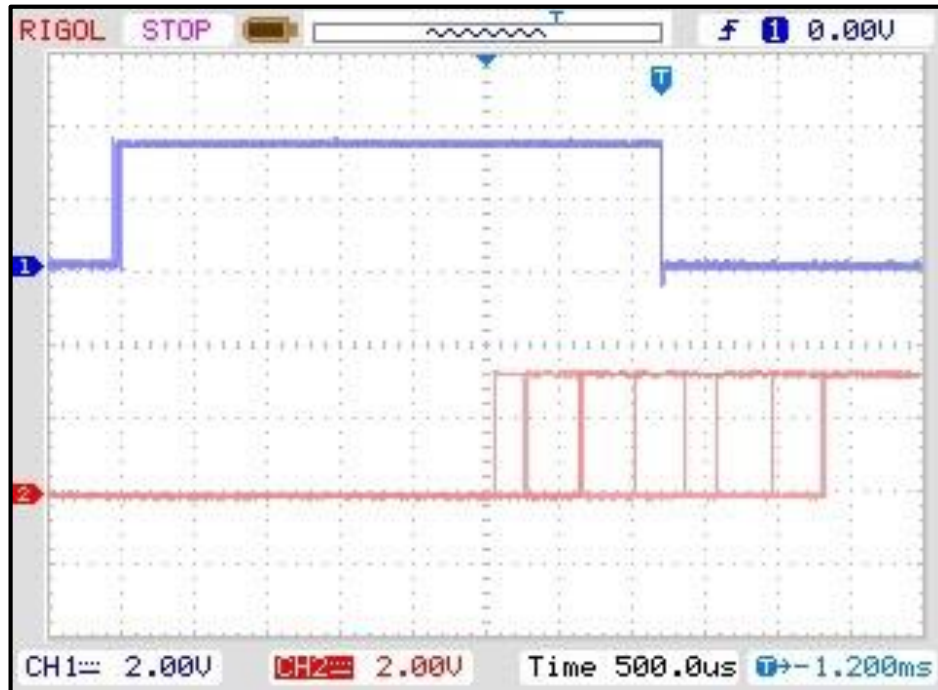


Figure 21 - Sending and Receiving RF signals (Measurements using an Oscilloscope)

In channel 1 (blue line) the changes from 0 to 1 represent the time instant when the command for the RF sending is given and in channel 2 (red line) it's possible to check when these signals are received. Unexpectedly, it was proved that the signal reaches the receiver at different time intervals. This cannot be due to different times of flight so the obvious conclusion is that the module responsible for the transmission is emitting the RF signals at different times. This must be due to a variation on the warm up/startup time of the module. Despite this, it was easily noticeable that these variations are somehow constant. This startup time is restricted to 8 different values with a minimum of 2,54 ms and a maximum of 4,78 ms. These values never change and that's the only reason why this project was still possible. In order to overcome this problem, instead of measuring the distance between the two devices just once, the system carries out 30 measurements and uses only the average of the 3 largest distances which will undoubtedly correspond to the 2.54 ms starting up time for probabilistic reasons.

The transmission of the ultrasonic signal was then delayed by 2.54 ms so both signals can leave the transmitter at the same instant. As an extra, this picture also proves that the jitter related to the RF system is so short that can almost be neglectable which means there is no uncontrollable variations that may negatively influence our measurement. This results in a high resolution that will allow the system to achieve very precise measurements.

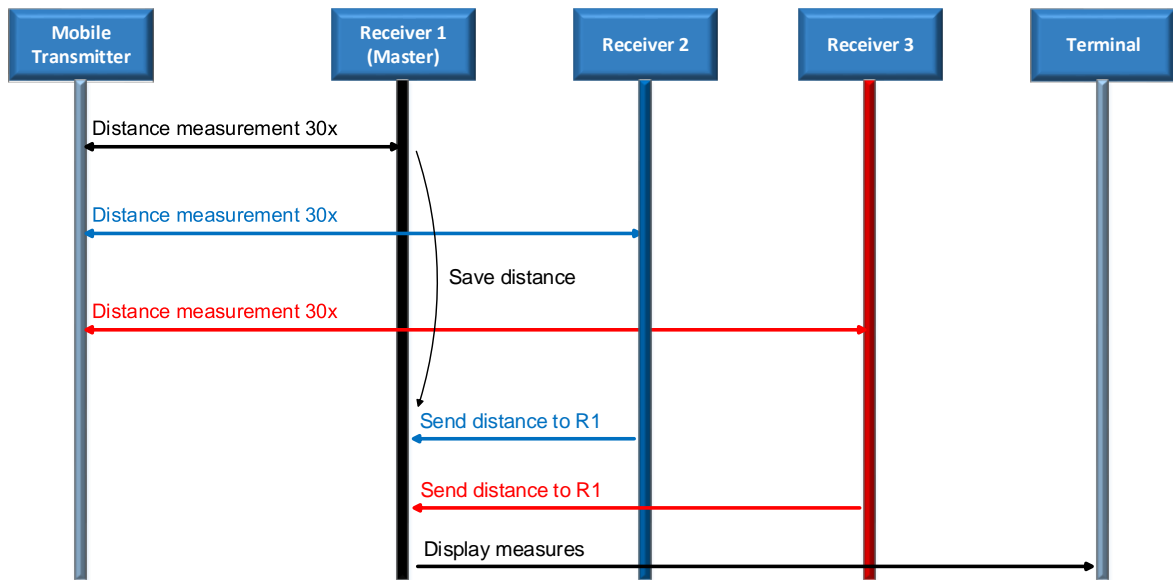


Figure 22 - System explanation diagram for 30 measurements

After obtaining the distances for the three receivers it is possible to determine the exact location of the transmitter using trilateration techniques.

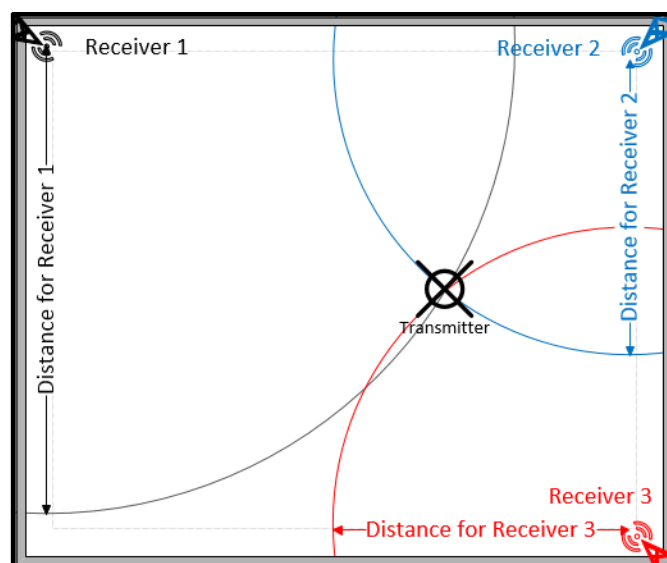


Figure 23 - Tracking the transmitter using Trilateration techniques

3.3.4 Error detection and handling

The system was thought in order to be able to handle some problems that may occur. The most common and expected situations that can compromise the functioning of this system are derived from the loss of a direct line-of-sight between the US transceivers or the overlap of simultaneous RF signals. The system's algorithm was designed based on time division multiplexing to avoid this frame collisions but some software enhancements were added to make this solution more resistant to this type of problems. Thus, devices are fully aware of the normal functioning of the system and therefore they know what to expect after each operation. If something is out of the ordinary they are programmed to respond or if that is not possible they will inform the user of an existing error.

Every time an RF frame is received, either in the transmitter or in the receivers, the information it contains is used to validate the process in progress. Adding to this, timers are used to verify long waiting periods that indicate the loss of expected US signals or RF frames. For example, if a receiver is told to start counting time by an RF frame, it will be expecting to receive the correspondent US burst within a predefined time (60 milliseconds). Timer0 is started when this RF frame reaches the receiver and if an US burst doesn't come within this time interval an error message is generated. The same can happen between measurements, if a receiver transmits an ACK before being done with its 30 measurements it will be waiting for the next measurement, in other words, it will be expecting an RF signal indicating the start of a new measurement. If a signal doesn't reach the receiver in time it may be because the first ACK never got to the transmitter and therefore it has to be resent. This is achieved by setting up another timer (timer1) that starts counting immediately after the first ACK and resends it after 60 ms. This procedure will only be done once since if it happens again the receiver will assume another problem and broadcast an error message.

The medium access, as previously stated, is done by time division multiplexing to ensure there are no overlaps between signals. Thus, when the transmitter is carrying out measures with one of the receivers the others are listening in an idle state. When the receiver 3 completes the 30 measures it transmits a RF frame containing the final estimated distance value. This frame is directed to the master receiver but it also indicate to the receiver 2 that all measures were concluded and so the medium is unobstructed. This will be listened as a green light for the receiver 2 to inform the master receiver of its own distance value.

The flowchart in figure 24 demonstrates some of these features together with the complete operation of the system. The receiver 3 is not included because its operation is identical to the receiver 2.

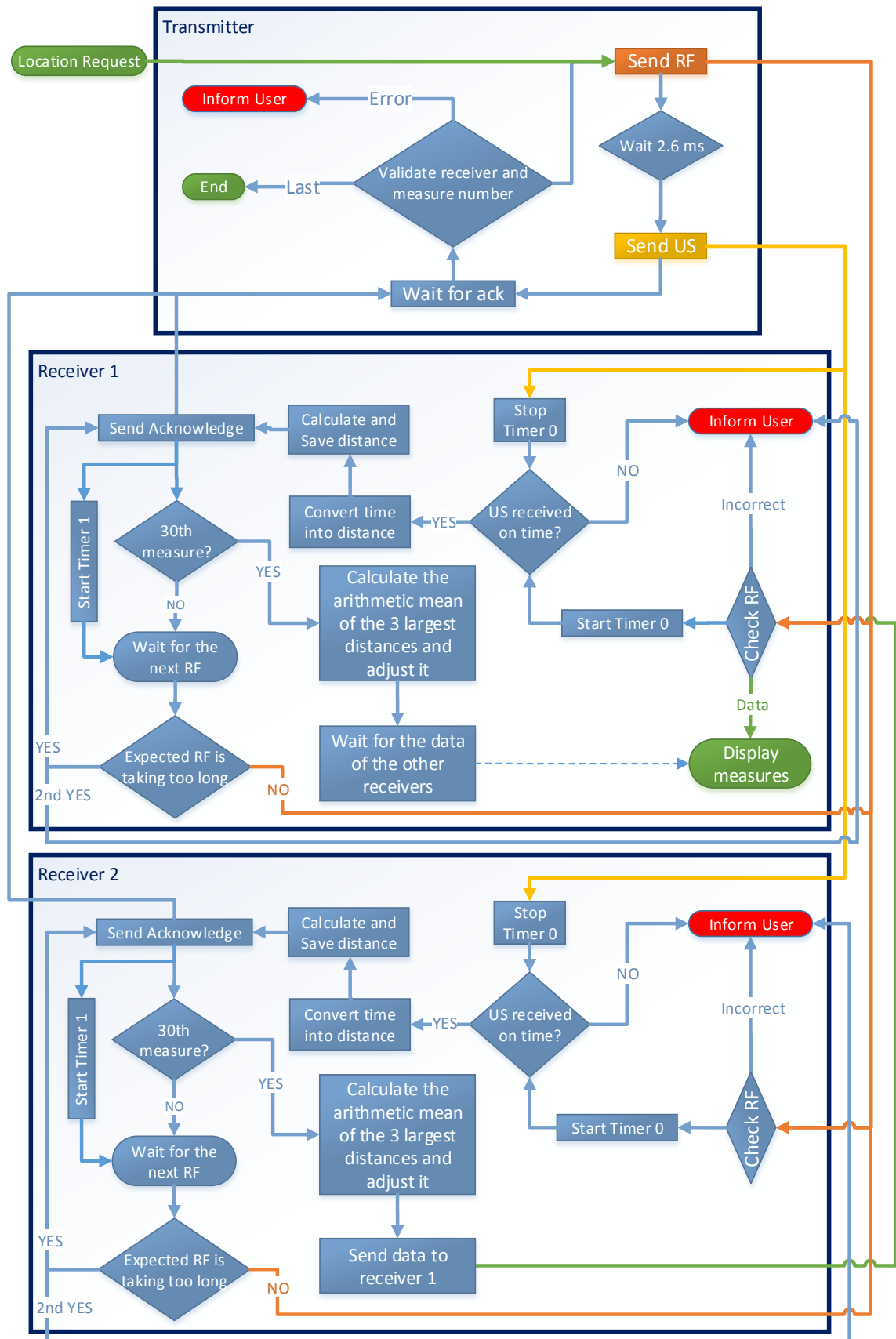


Figure 24 - Flowchart describing the system's operation

3.4 Software implementation

The developed solution is the result of a continuous effort on improving the system's performance along with the encountered limitations. The RF transceiver inconstant startup time increased the complexity of the software algorithm which by itself it's not an issue but now that 30 measurements are being carried out for each receiver the system is unsurprisingly more vulnerable to errors. In order to minimize any flaws that may occur it's crucial to have a good solution in terms of software implementation. A smart algorithm can guarantee a proper program execution avoiding overlaps and restricting the possible problems to physical nature flaws only. Here it's presented a summarized pseudo-code regarding the transmitter and the receiver number 1:

Transmitter

Initializations (Buffers for Tx and Rx, addresses, variables, etc.)

Configure USART, UMRFS I/O and the SPI communications with the MRF transceiver

Initialize the IEEE 802.15.4 transceiver and set up timers

```
while(1)
{
    if(Button is pressed)
    {
        START:
        Transmit RF message following the frame structure
        wait(2.6ms);
        Transmit US burst (during 2 ms)
        while(1)
        {
            if(RF received)
            {
                Validate message and compare it with expected receiver and
                measure number (ACK type, addresses and inform if wrong)
                if(Measure number == 30)
                    if(receiver number == 3) end program
                else
                    Receiver number++ and Measure number = 1
                    goto START
            }
            else
                Measure number++
            goto START
        }
    }
}
```

Receiver 1

Initializations (Buffers for Tx and Rx, addresses, variables, etc.)

Configure USART, UMRFS I/O and the SPI communications with the MRF transceiver

Initialize the IEEE 802.15.4 transceiver and set up timers

START:

```
while(1)
{
    if(Measure number>1 and timer 1> 80ms) Expected measure didn't arrived
    goto RESEND ACK or inform user of the issue if it repeats
    {
        if(RF received)
            if(Validate message( Measure type, src and dst address))
                start timer 0;
            else goto START
        while(1)
        {
            if(US received)
                Read and convert timer 0 register to decimal
                Calculate distance and save measure
                RESEND ACK:
                Send an ACK RF signal to the transmitter
                if(Measure number == 30)
                    Choose the 3 largest values and adjust them
                    while(1)
                        if(RF received check if its data type)
                            Print values from all the receivers
                        else
                            Measurement number ++;
                            Start timer 1
                            goto START
                else if(US takes longer than 80ms) inform user
        }
    }
}
```

All the code development was done resorting to the MPLAB IDE software program that is widely used to develop applications for Microchip microcontrollers and digital signal controllers. Its main advantage lies in providing a single integrated environment to program on embedded microcontrollers. This code was developed in C/C++ (programming language) and then compiled in a hex file. This file was written in the PIC18F26k20 flash memory using a PIC bootloader tool. In this case the ds30 Loader by MG Digital solutions was the chosen software because it is simple, easy to use and performs its tasks perfectly.

3.5 System implementation in a supermarket

The initial idea was to create a versatile system that could be applied in different contexts and serve diverse applications. However, the system has limitations derived from the technologies in use, particularly due to the usage of ultrasounds. The fact that ultrasounds can't penetrate obstacles can work in the system's benefit but is also a limitation that must be taken into account. If the system is intended to be applied in a supermarket's environment it's extremely important to consider that normal supermarket shelves constitute obstacles that will certainly reflect the ultrasonic signals. This means that a normal application of the system with ceiling mounted receivers and transmitters attached to the supermarket carts will generate a lot of undesired reflections that will undoubtedly jeopardize the system's functioning. Another issue of this solution is related to the limited range of the ultrasonic transceivers (20 meters maximum) and also their low directivity which may not be sufficient to cover all the area of a large supermarket. In order to solve these problems it's necessary to deploy multiple receivers.

The proposed solution is to mount two receivers for corridor, one at each end and in high positions. The normal shopping carts are wide enough to place one of the developed transmitters in one side thus avoiding people to obstruct most of the US signals. The RF signals overlap is handled by attributing different addresses to each device and by dividing the transmission moments in time. Thus, if the software is running correctly it will be impossible for two RF frames to be transmitted close to one another and cause an overlap.

With respect to the ultrasonic signals, the shelves would keep them safe inside the corridors preventing them from ruining the measurements of other receivers. The US reflections that will occur can be easily ignored since the only measurement of interest is the one corresponding to the shortest arriving time. Anyway, it would be advised to create a correlation between the US and RF signals of some sort and possibly in the future the US signals can be encoded so they can be differentiated from each other and even be transmitted with less power without having noise interference. This way, it would be possible to cover a large area without major contrarities and preventing all the expected complications.

The figure 25 demonstrates how the receivers could be disposed in order to cover all the area of a supermarket. The deployment of these receivers must be adjusted in number and location accordingly with the size and shape of that area so that there be no area left uncovered and in a way that can assure a clear line-of-sight with at least three devices in every location of the supermarket.



Figure 25 - Receivers arrangement inside a supermarket [25]

4. Results

This chapter will describe the tests performed on this indoor location system and presents the achieved results. These tests were carried out in two different places for better demonstrating the behavior of the system in different conditions and to get a more detailed study in real life environments. The first place was a large gym that was generously ceded for these tests by the University of Aveiro. This place was chosen due to its large dimensions and the absence of obstacles which allowed the test of the system up to its maximum range in a “clean” and ideal situation. The second place was a library called Mediateca which is also part of the same university, an indoor location with a configuration rather similar to the intended application. Thus, the shelves in the library will help us simulating what would happen in a normal supermarket giving us the idea of the system’s performance in such scenario.

In order to best understand our system’s current situation some previous tests were executed in the laboratory. This performance tests included the measurement of the power consumptions as well as the directivity of the system for two different power supply voltages because, as shown further in this document, they have a direct influence on the transmitter’s directivity.

4.1 Power consumptions

The power consumptions were measured using a current probe with the help of an oscilloscope and a fluke 287 digital multimeter. The following tables contain all the relevant information concerning the system’s power consumption:

US Transmitter		
Supply voltage	12V	17,5V
Standby	20 mA	35 mA
Transmitting	20 mA	38 mA

Table 8 - Power consumptions of the US transmitter

US Receiver

Supply voltage	12V
Standby	11 mA
Receiving (1 meter)	13 mA

Table 9 - Power consumptions of the US Receiver

μMRFs module

Standby (Transceiver OFF)	16 μA
Transceiver ON	23 mA Tx, 19mA Rx

Table 10 – Power consumptions of the μMRFs module

Combined power consumption

	Transmitter	Receiver
Standby	20 mA	11 mA
Receiving RF	39 mA	30 mA
Transmitting RF	43 mA	34 mA
Receiving US	-	13 mA
Transmitting US	20 mA	-

Table 11 - Combined power consumption for a supply voltage of 12V

4.2 Directivity

After measuring the received signal power at different but equidistant (1 meter) points from the transmitter in the laboratory it was possible to trace an approximate sketch of the transmitter's directivity. In figure 26 it's presented the appearance of the lobes that represent the signal strength transmitted in different directions.

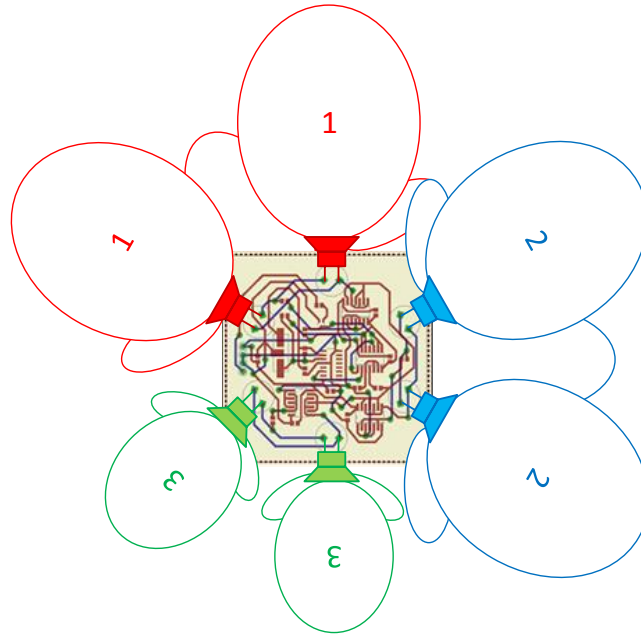


Figure 26 - Transmitter's directivity sketch

The transceivers represented in the same color are connected in parallel. Let's number the pairs by pair 1 (red), pair 2 (blue) and pair 3 (green). It was easily noticeable that the power spread by the three pairs wasn't even. The pairs number 1 (red) and 2 (blue) were favored in relation to the number 3 (green). There is a big disparity between them. However, after increasing the supply voltage from 12V to 18V this difference is shortened leaving the three pairs almost identical thus achieving a more omnidirectional transmission. This indicates an insufficient power supply voltage (when powered at 12V) putting aside any construction or design problem.

4.3 Measurements in a clean environment

A clean environment represents the ideal conditions for the operation of the system. In this case it is intended to test the system in open space, free of any possible intrusions and obstacles. For that reason the gym was the obvious choice for carrying out these tests. All values were read through the realterm serial capture software, a terminal specially designed for capturing, controlling and debugging data streams [26].

4.3.1 Measurements carried out between one transmitter and one receiver

Here are presented the results that were obtained using only one transmitter and one receiver inside the gym with a room temperature of 22°C. This test allowed to determine the repeatability and accuracy of the system as well as its maximum and minimum range. For that, the two devices were placed 1 meter above the ground and pointing at each other over a straight line. The transceiver that was used was the one that presented the highest transmission power. Two supply voltages were tested (12V and 17.5V) and five measurements were taken for each distance. All values are presented in centimeters.

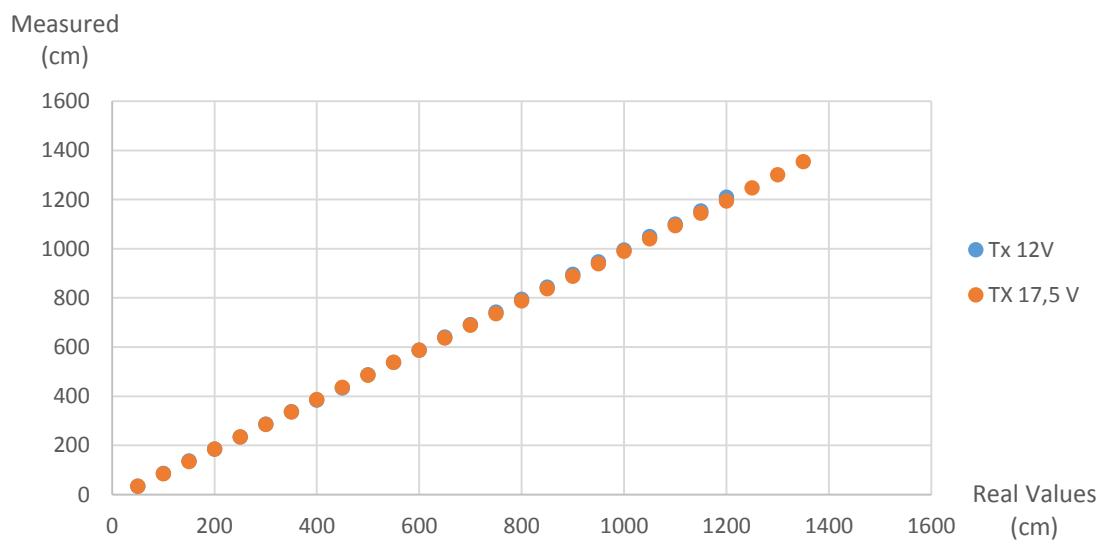
REAL VALUE	MEASUREMENTS (CM)					AVERAGE	ERROR
	1st	2nd	3th	4th	5th	(cm)	(cm)
50	34	34	34	33	34	34	16
100	86	86	85	85	86	86	14
150	136	136	136	136	136	136	14
200	185	185	185	185	185	185	15
250	235	235	231	235	235	234	16
300	286	286	287	286	286	286	14
350	337	337	337	337	336	337	13
400	384	386	383	383	386	384	16
450	435	434	434	434	435	434	16
500	488	488	485	488	484	487	13
550	537	538	538	538	537	538	12
600	587	588	587	584	587	587	13
650	639	641	641	637	640	640	10
700	690	691	691	691	691	691	9
750	743	743	742	742	741	742	8
800	794	795	794	795	794	794	6
850	844	843	843	844	842	843	7
900	896	894	895	896	895	895	5
950	946	946	946	948	946	946	4
1000	994	993	994	994	993	994	6
1050	1048	1049	1049	1049	1048	1049	1
1100	1100	1100	1101	1100	1101	1100	0
1150	1153	1154	1156	1153	1154	1154	-4
1200	1209	1207	1209	1211	1209	1209	-9

Table 12 - Measurements obtained for a supply voltage of 12V

REAL VALUE	MEASUREMENTS (CM)					AVERAGE	ERROR
	1st	2nd	3th	4th	5th	(cm)	(cm)
50	33	34	33	33	33	33	17
100	84	84	84	84	84	84	16
150	134	134	133	134	134	134	16
200	185	185	185	185	185	185	15
250	234	234	234	234	234	234	16
300	285	285	286	285	285	285	15
350	336	336	336	336	336	336	14
400	386	386	387	386	386	386	14
450	436	436	437	436	436	436	14
500	487	486	486	486	486	486	14
550	537	537	537	537	537	537	13
600	587	587	587	587	587	587	13
650	637	636	637	636	637	637	13
700	688	689	688	688	688	688	12
750	737	736	736	736	737	736	14
800	788	787	787	787	787	787	13
850	837	837	837	837	837	837	13
900	887	888	887	888	888	888	12
950	940	939	940	939	939	939	11
1000	989	989	989	990	989	989	11
1050	1040	1041	1040	1040	1040	1040	10
1100	1094	1093	1093	1093	1094	1093	7
1150	1143	1143	1145	1143	1144	1144	6
1200	1195	1193	1195	1193	1195	1194	6
1250	1246	1245	1247	1249	1246	1247	3
1300	1301	1299	1302	1300	1300	1300	0
1350	1353	1352	1351	1353	1354	1354	-4

Table 13 - Measurements obtained for a supply voltage of 17.5V

Chart 1 - Transmitter in different supply voltages comparison



Based on the previous tables is possible to state that the measurements have good repeatability as individual measurements for each distance don't differ by more than 2 or 3 centimeters. However, the average values is not very accurate when compared to the real distance. During these tests, it has been found a maximum deviation of 17 cm on the estimated distance for the minimum range limit. It was also possible to notice that, for very large distances, the US signal can only be detected in a restricted area and so a small angular deviation in the transceivers orientation may threaten the US detection. This results in somewhat incoherent values when the system is close its maximum range and it's related to the transmission power and the directivity of the US transceivers which may therefore impair the number of receivers needed for a given application.

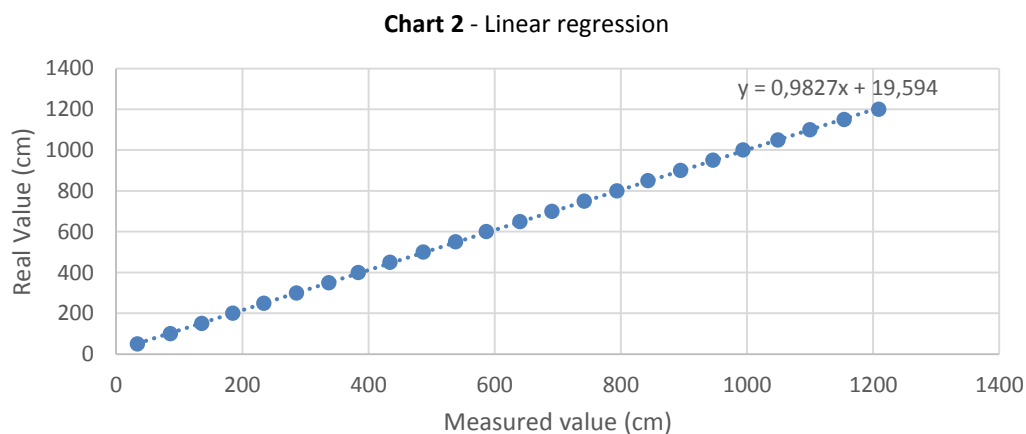
Another thing worth of pointing out is that the deviation from the real distance decreases linearly with the distance and that no differences are perceptible between a supply voltage of 12V and 17.5V except that the maximum range increased by 1.5 meters.

These deductions led to the next section which is about adjusting the values following a mathematical model.

4.3.2 Mathematical adjustment

After analyzing the obtained results it was possible to calculate a mathematical adjustment in order to approximate the results taken by the system to the real distance values thereby improving the performance of the system.

This mathematical approximation was obtained through a linear regression based on the previous results. Thus, the experimental values that were obtained (for 12V of supply voltage) are applied to a mathematical regression of type $y = mx + b$ in order to calculate m and b, where Y are the real values and X the measured results.



The resulting equation is:

$$y = 0,9827x + 19,594$$

It is now possible to use this approximation for future measurements by replacing X for the measured values and calculating Y. This will result in a smaller error as it can be verified in the next table.

REAL VALUES (CM)	MEASURED VALUES (CM)	VALUES AFTER ADJUSTMENT (CM)	OLD ERROR (CM)	NEW ERROR (CM)
50	34	53	16	3
100	86	104	14	4
150	136	153	14	3
200	185	201	15	1
250	234	250	16	0
300	286	301	14	1
350	337	351	13	1
400	384	397	16	-3
450	434	446	16	-4
500	487	498	13	-2
550	538	548	12	-2
600	587	596	13	-4
650	640	649	10	-1
700	691	699	9	-1
750	742	749	8	-1
800	794	800	6	0
850	843	848	7	-2
900	895	899	5	-1
950	946	949	4	-1
1000	994	996	6	-4
1050	1049	1050	1	0
1100	1100	1101	0	1
1150	1154	1154	-4	4
1200	1209	1208	-9	8

Table 14 - Comparison of the measurements and errors after adjustment

Chart 3 - Comparison after adjustment

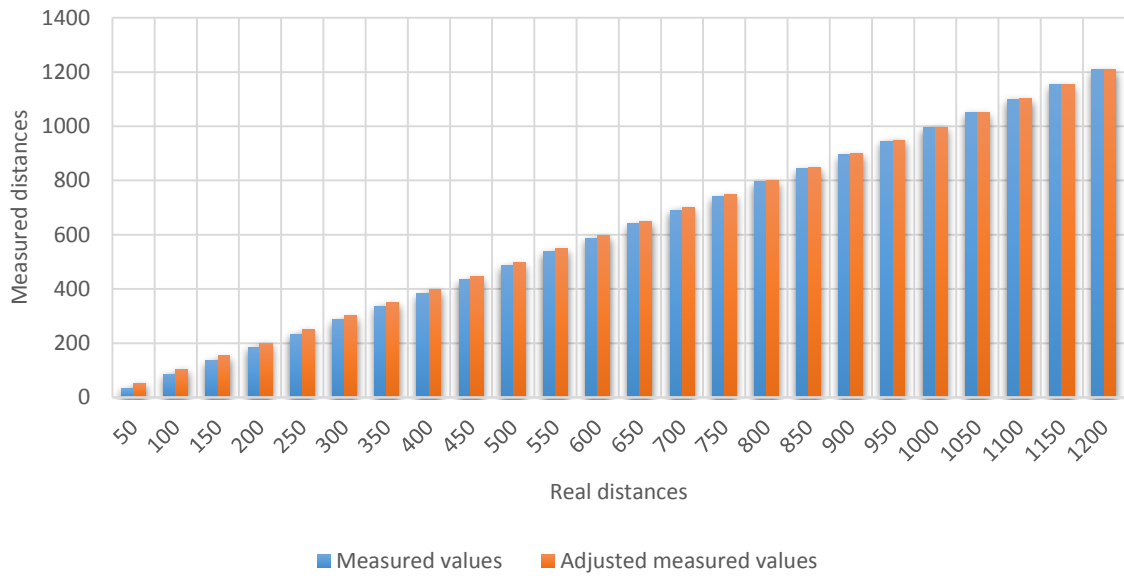
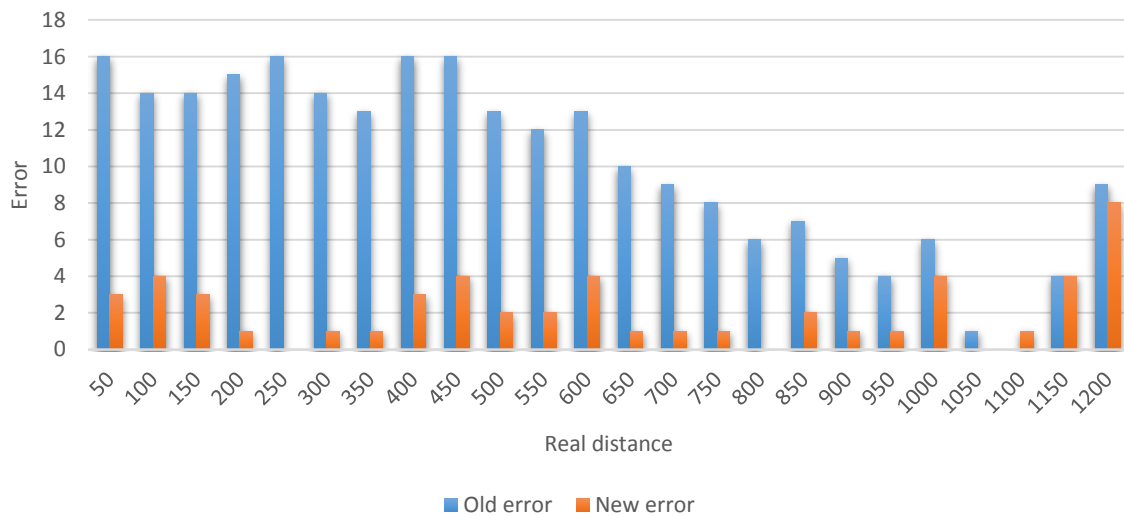


Chart 4 - Comparison of the deviation before and after adjustment



What this adjustment does is basically add to the measured value a quantity that is inversely proportional to the distance thus compensating the experimental error found before in favour of the system.

The absolute error after the adjustment does not exceed the 5 centimeters which makes it compatible with the intended application and its demands. Nevertheless, these results only reflect the system's performance for ideal conditions in a clean environment.

4.3.3 Measurements for each pair of transceivers individually

This part of the tests will be used to compare the three pairs of transceivers (see figure 26) with regards to their maximum range and measured values. Two different supply voltages were applied to the transmitter in order to better understand the directivity issue described in the beginning of this chapter. The values in green correspond to a supply voltage of 12V and the values in orange were obtained for 17,5V. The layout of the test was the same as before with the devices pointing straightly at each other and placed 1 meter above the ground. The overall conditions like humidity and temperature also remained unchanged.

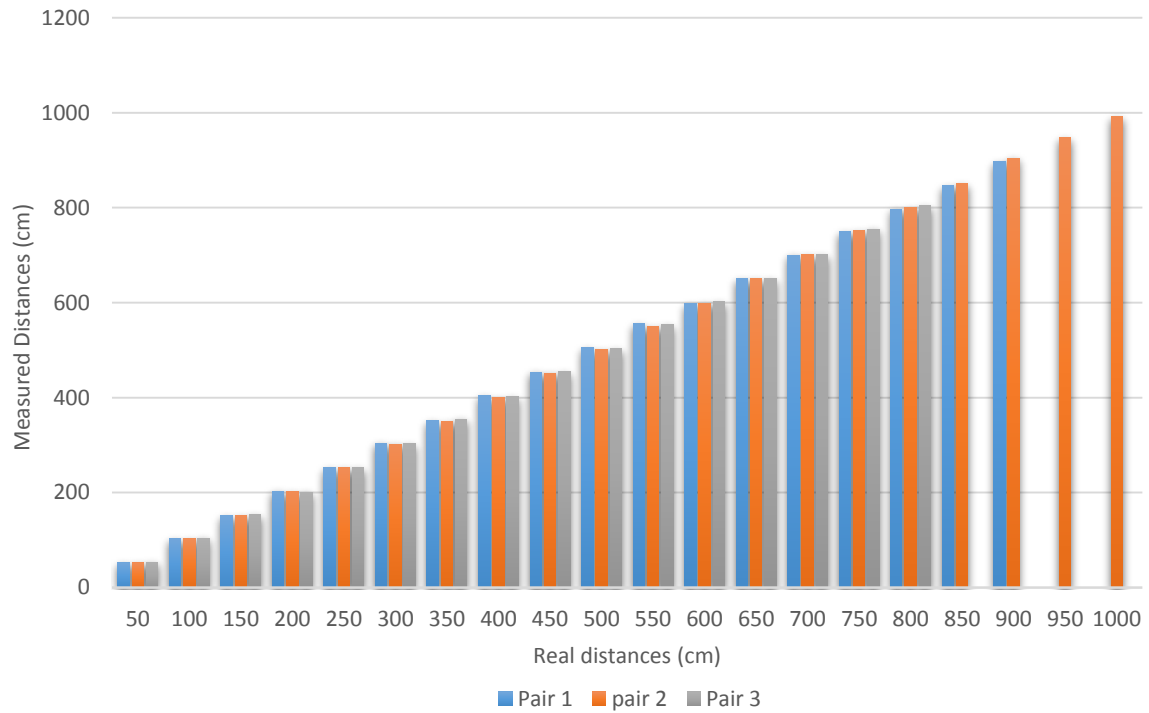
Real distance	Measurements for the pair 1 (cm)						
	1st	2nd	3th	4th	5th	Average	Deviation
50	52	53	52	52	52	52	2
100	104	103	103	103	104	103	3
150	152	152	152	152	152	152	2
200	203	202	202	203	203	203	3
250	252	252	252	253	252	252	2
300	303	304	305	304	304	304	4
350	352	352	352	351	351	352	2
400	403	404	404	404	404	404	4
450	455	453	455	455	454	454	4
500	507	507	506	506	506	506	6
550	556	555	557	555	555	556	6
600	604/598	605/597	604/598	604/597	605/598	598	2
650	653/649	652/648	654/650	652/650	654/650	650	0
700	701	700	701	701	699	700	0
750	749	749	749	749	748	749	1
800	796	797	797	797	798	797	3
850	846	846	846	846	846	846	4
900	895	896	897	897	898	897	3
950							

Table 15 - Measurements for the pair 1

Real distance	Measurements for the pair 2 (cm)						Measurements for the pair 3 (cm)			
	1st	2nd	3th	4th	5th	Average /Error	1st	2nd	3th	Average /Error
50	52	52	52	52	52	52 / 2	53	53	53	53 / 3
100	103	103	103	103	103	103 / 3	104	104	104	104 / 4
150	152	152	152	152	152	152 / 2	154	153	153	153 / 3
200	202	202	202	202	203	202 / 2	203/201	203/201	203/201	201 / 1
250	252	252	252	252	252	252 / 2	255/253	257/253	257/253	253 / 3
300	302	302	302	302	301	302 / 2	307/303	307/303	307/303	303 / 3
350	350	349	350	350	349	350 / 0	358/355	358/355	358/356	355 / 5
400	399	400	400	400	400	400 / 0	402	402	401	402 / 2
450	453	452	452	453	452	452 / 2	454	455	455	455 / 5
500	501	501	500	500	501	501 / 1	504	503	503	503 / 3
550	550	550	549	549	550	550 / 0	553	554	554	554 / 4
600	599	599	599	599	599	599 / 1	603	602	602	602 / 2
650	650	650	650	649	649	650 / 0	651	651	651	651 / 1
700	702	701	701	703	702	702 / 2	702	702	702	702 / 2
750	752	750	750	751	750	751 / 1	756	755	755	755 / 5
800	800	801	800	800	801	800 / 0	804	804	804	804 / 4
850	849	849	850	850	850	850 / 0				
900	905	905	904	902	903	904 / 4				
950	948	946	947	947	948	948 / 2				
1000	990	992	992	990	991	991 / 1				

Table 16 - Measurements for the pair 1 and 2

Chart 5 - Comparison between the three pairs

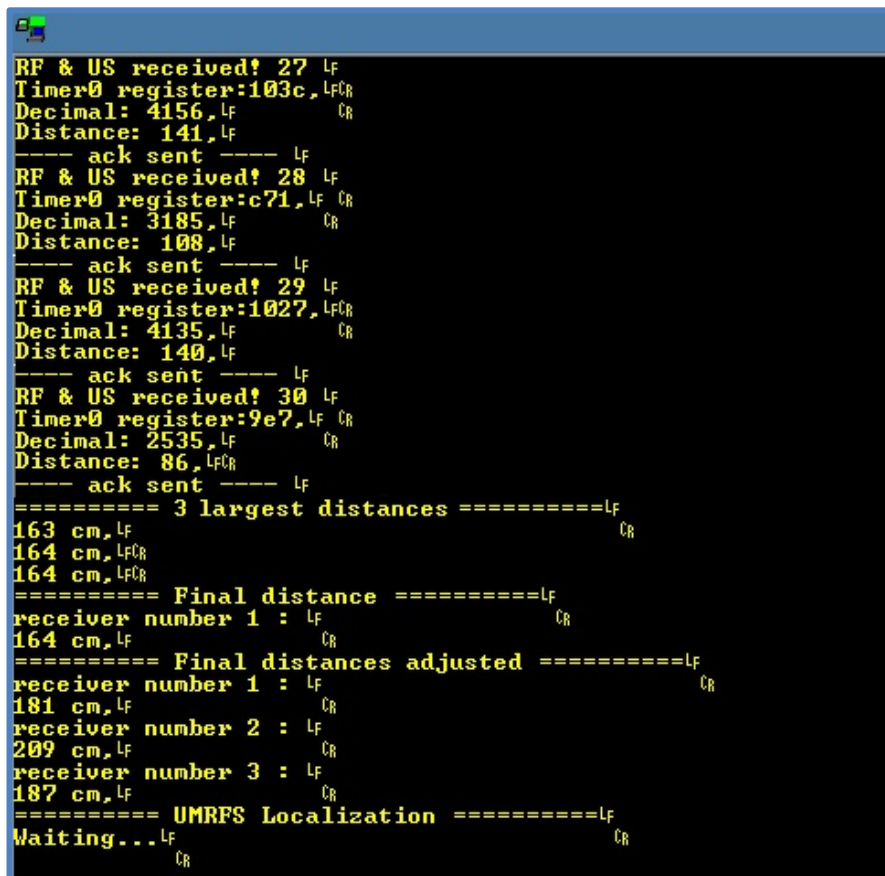


Here it's possible to emphasize the fact that our maximum absolute error is around 6 cm which goes according to the previous test. Another noteworthy point is that there is a big difference in the maximum range for the two supply voltages with respect to the pairs of transceivers number 1 and 3 as it would be expected after the directivity test. For 17.5V, the maximum range of the pairs 1, 2 and 3 is 9, 10 and 8 meters respectively which suggest that for a higher voltage the difference between them would decrease even more.

Concerning the measurements, it is now safe to assume that there is no difference between the values taken from the three pairs (as expected) since, as it can be noticeable in chart 5, the average does not change for a particular distance.

4.3.4 Measurements for one transmitter and three receivers

In terms of conceptualisation it is important to point out that in this part of the tests the full program algorithm is put to the test because from now on the three receivers will be correlated to the same time instant for the first time. In these experiments, as it was previously mentioned, all values were read using the Real Term serial terminal. Here is the appearance of the terminal connected to the receiver number 1 displaying informative messages after a measurement:



```
RF & US received! 27 LF
Timer0 register:103c, LF CR
Decimal: 4156, LF
Distance: 141, LF
---- ack sent ---- LF
RF & US received! 28 LF
Timer0 register:c71, LF CR
Decimal: 3185, LF
Distance: 108, LF
---- ack sent ---- LF
RF & US received! 29 LF
Timer0 register:1027, LF CR
Decimal: 4135, LF
Distance: 140, LF
---- ack sent ---- LF
RF & US received! 30 LF
Timer0 register:9e7, LF CR
Decimal: 2535, LF
Distance: 86, LF
---- ack sent ---- LF
===== 3 largest distances ===== LF
163 cm, LF
164 cm, LF CR
164 cm, LF CR
===== Final distance ===== LF
receiver number 1 : LF
164 cm, LF
===== Final distances adjusted ===== LF
receiver number 1 : LF
181 cm, LF
receiver number 2 : LF
209 cm, LF
receiver number 3 : LF
187 cm, LF
===== UMRFS Localization ===== LF
Waiting... LF
CR
```

Figure 27 - Terminal of the receiver 1 after a measurement

In figure 27 is possible to check the last 4 measurements performed from a total of 30 as well as the final results for the three receivers. For each individual measurement the program prints out the content of the timer (timer0 register of the PIC18F26K20), its respective conversion to decimal and the distance calculated from these values. It also provides essential information to the user about the reception of signals, the sending of acknowledge messages and about any error that may occur.

In figure 28 it's possible to see the three receivers and the one transmitter that compose the whole system.

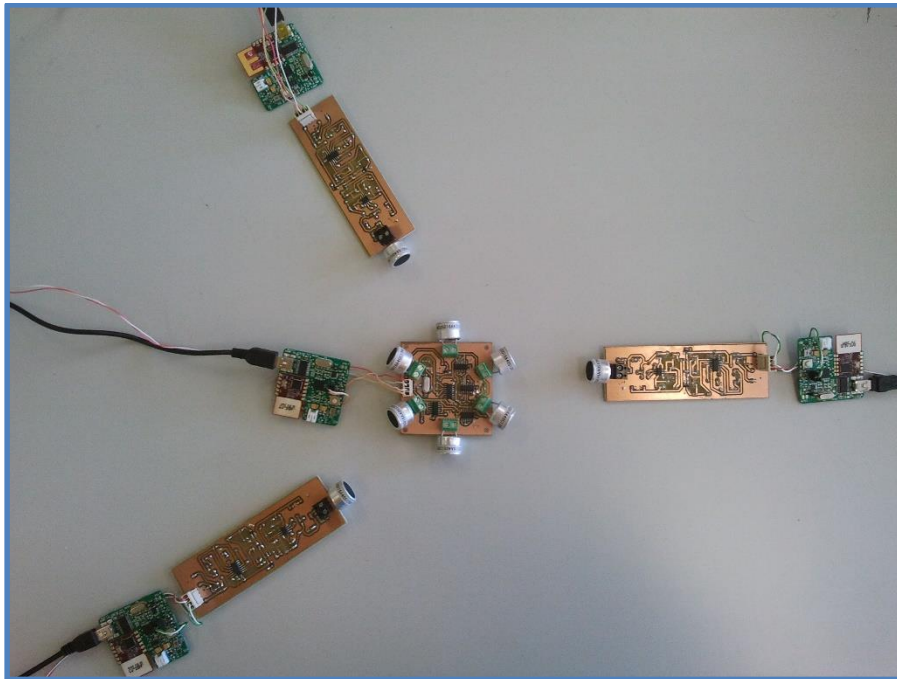


Figure 28 - System appearance

The system was initially thought to have a mobile transmitter and fixed receivers placed in fixed and referenced positions. At this point, tests were focused in that context that most resembles the scenario of a possible future application. The receivers were placed at 3.7 meters of each other forming an equilateral triangle as represented in figure 29. The transmitter was moved around this area and tracked with a few measurements that are presented in table 17.

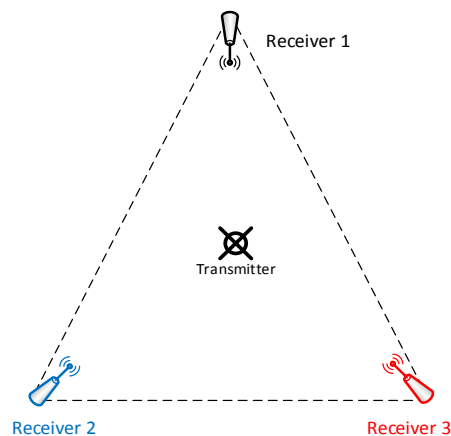


Figure 29 – Arrangement of the fixed receivers

	Receiver 1 (cm)			Receiver 2 (cm)			Receiver 3 (cm)		
	Real distance	Measured distance	Error	Real distance	Measured distance	Error	Real distance	Measured distance	Error
1 st	298	293	5	258	257	1	115	112	3
2 nd	205	206	1	228	224	4	192	187	5
3 th	187	180	7	286	292	6	166	159	7
4 th	270	266	4	100	99	1	309	302	7
5 th	185	180	5	229	225	4	209	203	6

Table 17 - Measurements for three receivers

The maximum error increased by 2 centimeters due to a change in the room temperature which had a direct influence in the propagation speed of the ultrasonic waves and a consequent interference after the mathematical adjustment. This adjustment must be accordingly to the environment conditions otherwise there will be a precision loss. Thus, the measurement of the external conditions with the already included temperature sensor in the μ MRFs board (referred in the [chapter 5.2](#)) will be of great importance in the future because it will allow to make a proper adjustment according to the ambient temperature.

It is also believed that the fact of not having the sensors pointing directly at each other had some negative influence in the obtained values.

4.4 Real case study

4.4.1 Measurements in a “real life” environment

Following the presented experiments, the system was tested inside the Mediateca (a small library with bookshelves, tables and chairs) for a better approximation of a real case scenario. These obstacles will simulate some of those found in real life environments giving us a good perspective of the system’s performance in the presence of non-ideal conditions.

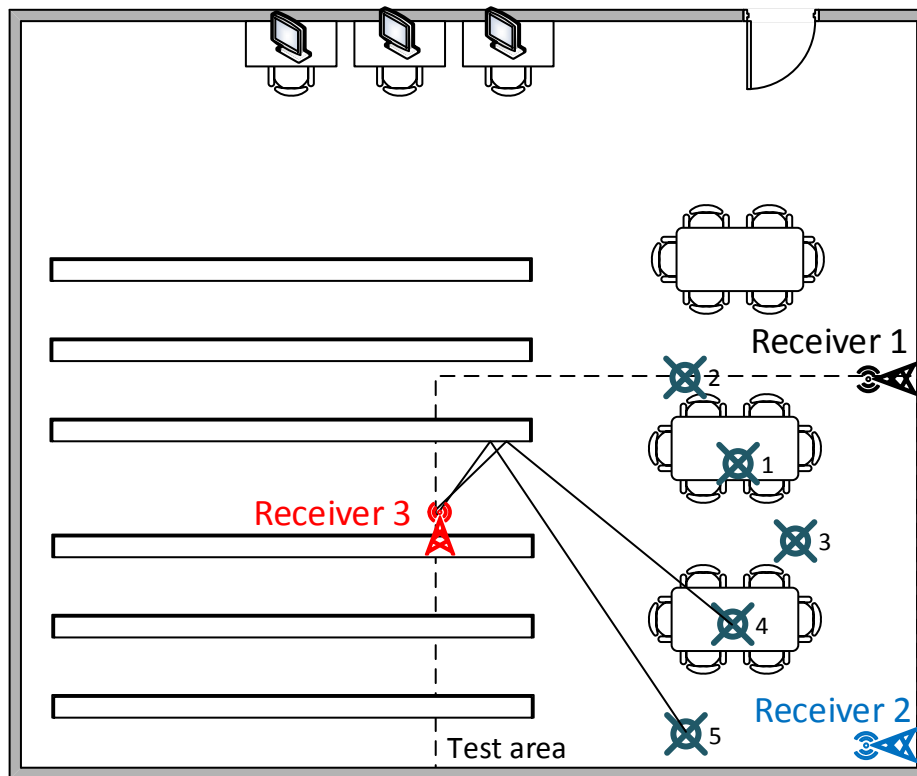


Figure 30 - Mediateca testbed

In order to verify the results obtained in the absence of a clear line-of-sight the receiver number 3 was placed between bookshelves as shown in figure 30. In that position it is known that for the test points number 4 and 5 the operation of the system will be compromised leading us to fallacious results or more likely to error messages. This test was carried out on a hot day with a room temperature of about 24°C. The obtained results on the described conditions are presented in the table 18. Please note that the distances in figure 30 may not be consistent with those in table 18.

	Receiver 1 (cm)			Receiver 2 (cm)			Receiver 3 (cm)		
	Real distance	Measured distance	Error	Real distance	Measured distance	Error	Real distance	Measured distance	Error
1 st	134	127	7	296	286	10	252	245	7
2 nd	128	122	6	407	398	9	274	265	9
3 th	181	174	7	198	191	7	321	312	9
4 th	314	305	9	158	149	9	≈220*	387*	167
5 th	407	397	10	135	130	5	≈298*	457*	159

Table 18 - Measurements in Mediateca (*No line-of-sight)

The Mediateca was undoubtedly the test area with the highest room temperature and the worst general conditions that this system had to face until this point. That might serve as explanation to the highest deviation found so far. A maximum absolute error of 10 centimeters can't be neglected but it's still within the proposed limits and it's not considered relevant for the concerned application.

The values in a light blue background were obtained without a clear line-of-sight so the real distance is just an approximation and the presented values must be resulting from reflections on the bookshelves. It is noteworthy that, for a few times, these measurements resulted in an output error message originated on the receiver 3 saying that the US reception timed out, i.e., the US burst never reached the receiver.

4.4.2 Measurements in a corridor

This experiment was performed in a corridor of the Electronics Telecommunications and Informatics Department of the University of Aveiro. Two receivers were placed at a distance of 10 meters from each other and measurements were obtained for different positions of the transmitter as indicated in figure 31.

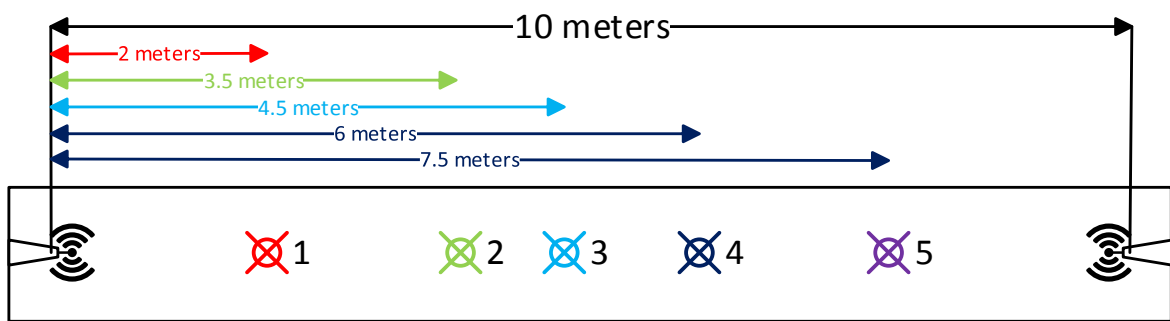
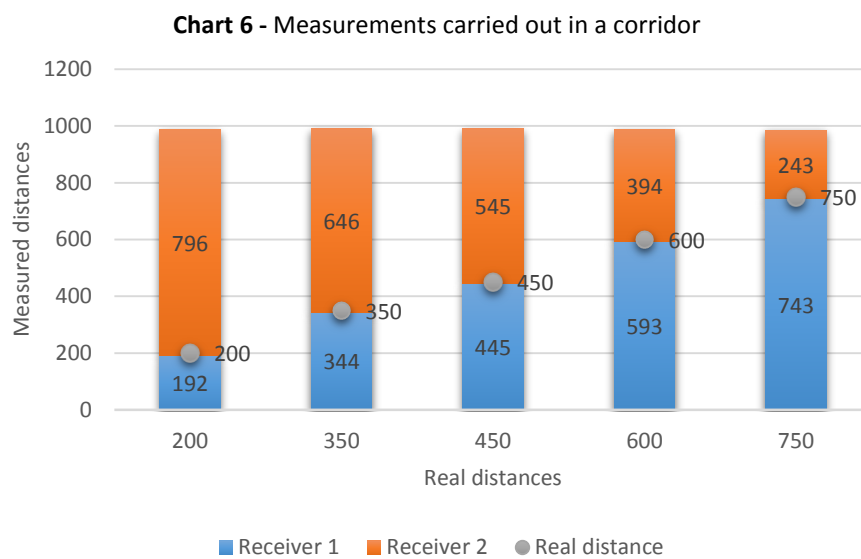


Figure 31 - Corridor measurements arrangement

	Receiver 1 (cm)			Receiver 2 (cm)			Sum
	Real distance	Measured distance	Error	Real distance	Measured distance	Error	
1 st	200	192	8	800	796	4	988
2 nd	350	344	6	650	646	4	990
3 th	450	445	5	550	545	5	990
4 th	600	593	7	400	394	6	987
5 th	750	743	7	250	243	7	986

Table 19 - Measurements in a corridor



As it was mentioned before, one possibility of implementing this system into a supermarket would be to monitor the movement of the shopping carts individually for each corridor. This test was realized to verify the credibility of this operation method. Some problems associated with the corridor walls could be anticipated but these concerns turn out to be unsubstantiated. The system operated smoothly under these circumstances and the accuracy of the achieved results is very satisfactory. Despite that, it is clear that all measured values are a little lower than desired so their sum is also under the 10 meters. A suggested improvement to compensate this factor in an easy way would be to make a specific adjust for this scenario rather than using the previous mathematical model. An accuracy of this order would certainly be enough to distinguish the exact spot where the supermarket cart is within a 10 meters range thus confirming the viability of this system. A correlation of the two receivers can be used here to verify and improve the quality of the measurements. In this case, the localization could be done with a coordinate system of only one coordinate.

5. Conclusions and future work

5.1 Conclusions

This dissertation starts by giving a general insight of the most relevant existing indoor location systems that are currently trying to fill, what still is a market niche, but with a large margin of progression. A description of their operation is given together with a discussion about the main differences between them. On that ground, a system capable of providing a fine-grained localization in indoor environments was idealized and conceived. All the fundamental hardware for the proposed solution has been successfully developed and the major upset worth of reference is the directivity issue on the transmitter derived from limitations of the transceivers and power supply restrictions. On the other hand, the software implementation ensures a reliable operation and program execution, free of unexpected interruptions with the exception of those derived from unavoidable physical restrictions like the case of an obstructed US burst. In this unlikely event, the interruption is treated by informing the user of the anomaly with the correspondent error message.

The system's power consumption is low so the autonomy of these devices when battery-powered is perfectly suitable for most of the possible applications.

Concerning the obtained results, the system carried out measurements with great accuracy thus achieving a maximum error of 10 centimeters (in the worst case). This accuracy degree could be improved by making a proper adjustment accordingly with the environmental conditions. I believe that, after trilateration or multilateration, this system would be able to perform a fine-grained localization with a very good approximation of the estimated position to the actual one.

In conclusion, although still far from being a commercial product, a fully functional prototype was accomplished, which proves that the described method of localization is feasible (even being based upon a relatively simple and low cost method).

5.2 Future work

For future work it must be pointed out the implementation of the final step the final step of this project which is completing the position acquisition through trilateration methods in order to compute the final estimated positions. These geometric calculations can be done in relation to three or more reference points and can be realized for a coordinate system of two or three dimensions depending on the intended application. No additional data would be required, the system can already gather, provide and process all the necessary information. The main issue here would be the low capability of the PIC18F26K20 to perform mathematical operations and the limited memory space of this microcontroller. Those are very important restrictions that must be considered in order to complete this project. Therefore, in my opinion, it would be fundamental to replace this microcontroller for a more powerful one.

Regarding the improvement of the system, an issue worthy of greater attention is related to the directivity of the ultrasonic transmitter ([chapter 3.1.4](#)) which, at this point, is imposing a supply voltage higher than desired. This may be due to constraints in the integrated circuits that were used in the final stage of the transmitter's circuit where it was decided to place two transceivers in parallel. Thereby, the solution may lie in a few design modifications or, more dramatically, in changing the concept of the system in a way that transmitters are replaced by receivers and vice-versa. This new configuration would have the advantage of having the receivers as the mobile devices, something that makes more sense considering its lower power consumption. In terms of the directivity it's uncertain to say if the system would benefit with these alterations.

A simple voltage regulator from 12V to 5V can be used in the future to power both the US transmitter and the μ MRFs board thus eliminating the necessity of feeding the μ MRFs by USB which would be essential to make the transmitter completely mobile.

In order to make this system more efficient it would be indispensable to use a transceiver with a faster response or at least with a constant startup time so that it would only require to perform one measure instead of thirty. Furthermore, measuring the current temperature value with the already available temperature sensor embedded in the μ MRFs module and using it in the calculation of the speed of sound would certainly enhance the accuracy of the system.

There is also some aspects to improve at the software level such as the continuity of the program execution after some interruptions. The system must be capable of ditching any failed measurement that may occur and continue to perform his duties. Still at the software level it would be possible to measure the voltage controlling the gain of the AGC so the system would use that information to perform more or less measurements depending on the quality of the detected signal.

It is also of great interest to make this system scalable in the number of transmitters/receptors thus allowing auto-configuration after the inclusion and/or removal of the devices to/from the system. Posteriorly, this capacity of adaptation can be of great benefit to the system because it will allow, in an easy way, to adapt the number of receivers depending on the application scenario which will improve the performance of the system in the presence of obstacles.

Another possible complement for this system would be to use the accelerometer of the uMRFs module to calculate the velocity vector of the shopping carts. Thus, the system could adjust the number of measurements based on their velocity by performing less or more measurements depending if they are stationary or in motion, respectively.

In terms of energy management, in theory, it would be possible to charge the batteries of the mobile devices by converting the mechanical energy generated with the movement of the shopping carts into electric energy using an alternator (this process is called energy harvesting).

After having everything settled the next step will naturally be, testing the final system by deploying it in a real life environment.

6. Bibliography

[1] Nissanka Bodhi Priyantha, "The Cricket Indoor Location System", Dissertation Submitted to the Department of Electrical Engineering and Computer Science on May 19, 2005, University of Cambridge.

[2] Nissanka B. Priyantha, Anit Chakraborty, and Hari Balakrishnan, "The Cricket Location-Support System", MIT Laboratory for Computer Science, University of Cambridge.

[3] Adam Smith, Hari Balakrishnan, Michel Goraczko, and Nissanka Priyantha, "Tracking Moving Devices with the Cricket Location System", MIT Computer Science and Artificial Intelligence Laboratory, University of Cambridge.

[4] "Cricket v2 User Manual", [Online]. Available: <http://cricket.csail.mit.edu>. [Accessed: July 2014].

[5] Oliver J. Woodman and Robert K. Harle, "Concurrent scheduling in the Active Bat location system", University of Cambridge.

[6] Jeffrey Hightower and Gaetano Borriello, "Location Sensing Techniques", University of Washington, Computer Science and Engineering, Seattle, July 2001.

[7] M. Tavakoli and S. Yamamoto, "Human Tracking Devices: the Active Badge/Bat and Digital Angel / Verichip systems", ECE 399, Project paper #1, Oregon State University, 2003.

[8] Mike Hazas and Andy Hopper, "Broadband Ultrasonic Location Systems for Improved Indoor Positioning", IEEE TRANSACTIONS ON MOBILE COMPUTING, May 2006.

[9] Yasuhiro Fukuju, Masateru Minami, Hiroyuki Morikawa and Tomonori Aoyama, "DOLPHIN: An Autonomous Indoor Positioning System in Ubiquitous Computing Environment", IEEE Workshop on Software Technologies for Future Embedded Systems (WSTFES2003), pp.53-56, Hakodate, Japan, May 2003.

[10] Andy Ward, Alan Jones and Andy Hopper, "A New Location Technique for the Active Office", University of Cambridge Computer Laboratory.

[11] S. Yalavarthy, "An Analysis on Tracking User Location Systems", Department of Electrical & Computer Engineering, project under the guidance of Dr. Dale Callahan, University of Alabama.

[12] W. Zhang, J. Djughash, and S. Singh, "Parrots: A Range Measuring Sensor Network", Technical report, Robotic Institute in Carnegie Mellon University, 2006.

[13] Flávio Sá, "SLIUSM – Sistema de Localização e Identificação por Ultra-sons para Museu", Tese de Mestrado, Universidade de Aveiro, 2008.

[14] A. Willig, K. Matheus and A. Wolisz, "Wireless Technology in Industrial Networks", Proceedings of the IEEE, vol. 93, Junho 2005.

[15] Micro I/O serviços de electrónica, lda, [Online]. Available: <http://www.microio.pt>. [Accessed: July 2014].

[16] P. Bartolomeu and V. Baptista, uMRFs: a tiny wireless node, 0.1, Micro I/O serviços de electrónica, Lda, Oct. 2011.

[17] Pedro Miguel Capinha Germano do Mar, "Sensores e Actuadores Sem Fios Para Ambientes Habitacionais", Tese de Mestrado, Universidade de Aveiro, 2011.

[18] Microchip XLP technology, [Online]. Available: <http://www.microchip.com/pagehandler/en-us/technology/xlp/>. [Accessed: July 2014].

[19] Microchip, "28/40/44-Pin Flash Microcontrollers with nanoWatt XLP Technology", PIC18F23K20/24K20/25K20/26K20/43K20/44K20/45K20/46K20 Datasheet.

[20] "ZigBee® RF4CE", [Online]. Available: <http://www.microchip.com/pagehandler/en-us/technology/personalareanetworks/technology/zigbeerf4ce.html>. [Accessed: July 2014].

[21] Microchip, "2.4 GHz IEEE Std. 802.15.4™ RF Transceiver Module with PA/LNA and External Antenna Connector", MRF24J40MC Datasheet.

[22] Murata, Ultrasonic sensors, MA40 series Datasheet.

[23] Multicomp, Ultrasonic transceiver, MCUSD16A40S12RO Datasheet.

[24] Cadsoft Eagle software, [Online]. Available: <http://www.cadsoftusa.com/>. [Accessed: July 2014].

[25] Thomas Sincak, Display and packaging renderings gallery, “Complete Supermarket 3d Environment 3D Render”, [Online], Available: <http://www.behance.net/gallery/Display-and-packaging-renderings-gallery/1354009>. [Accessed: July 2014].

[26] Realterm Serial/TCP terminal, Open-Source software, [Online]. Available: <http://realterm.sourceforge.net/>. [Accessed: July 2014].

[27] Sedra & Smith, “Microelectronic Circuits”, 5th Edition, 2003.

[28] Haykin, Simon, “Communications Systems”, 4th Edition , John Wiley & Sons Inc, 2001.