Deployment of efficient wireless sensor nodes for monitoring in rural, indoor and underwater environments

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Deployment of Efficient Wireless Sensor Nodes for Monitoring in Rural, Indoor and Underwater Environments

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Abstract

There are many works related to the design and development of sensor nodes which present several applications. Wireless sensor networks can facilitate and improve some aspects of our daily lives. It is easy to think that if this type of device is so beneficial to us and to our environment, its price should be relatively cheap. But we can see that this is not true. Why these devices are so expensive? Would it be possible to develop devices with the same capabilities and lower prices? How can I make my low-cost sensor nodes?

This dissertation answers these questions and shows some of the many applications that sensor nodes may have. In this dissertation, we propose (and implement in some cases) the development of sensor nodes for environmental monitoring, from low-cost devices. For the implementation of a sensor node and network which joins all these nodes, it is important to know the environment where they will work. Throughout this dissertation, we present the research carried out for the development of sensors in three main application areas.

In the first of these areas, we present multisensor devices developed for environmental monitoring. The application of wireless sensor networks to the environment requires a study of how signals are affected depending on the distance, vegetation, ambient humidity, etc. We focus our developments on the fire detection in rural areas and on the control of pests in vineyards where the early detection of these events generates high economic savings. We also propose the development of a sensor network which will help us to reduce and prevent wolves' attacks and theft in livestock. Finally, within this group, we present a network to detect material anomalies in building and a sensor network which allows us to monitor the elderly or disabled people who move along with a group on a tour or activity.

The second group of applications is related to the monitoring of spaces in indoor environments. For this, we analyze the behavior of wireless signals in different scenarios. These results allowed us to extract a new method for designing wireless networks in indoor environments. Our method allows defining the best location of network devices and sensor nodes indoors saving 15% of the sensors needed.

Finally, we present a study on underwater freshwater communications based on electromagnetic waves, where we analyze the dependency of underwater communications as a function of working frequency, temperature, data transfer rates and modulation.

Related to underwater environment, we present two proposals. First one refers to the implementation of a sensor network for marine farms which allows us to reduce the amount of waste deposited on the seabed and reduce the percentage of wasted food. The second proposal is the development of two oceanographic sensors which allow us to control the amount of food and feces deposited in seabed and the water turbidity control in a very simple and inexpensive way.

All these developments and proposals have been preceded by a comprehensive study on the energy problems in wireless sensor networks. We have also presented several techniques which can be used to prolong the network lifetime and improve its stability.

Resumen

Existen muchos trabajos relacionados con el diseño y desarrollo de nodos sensores, donde se presentan gran variedad de aplicaciones. Las redes de sensores inalámbricos pueden facilitarnos y mejorar algunos aspectos de nuestra vida diaria. Es fácil pensar que si este tipo de dispositivo es tan beneficioso para nosotros y para el entorno donde vivimos, su precio debería ser relativamente barato. Pero podemos comprobar que esto no es así. ¿Por qué estos dispositivos son tan caros? ¿Sería posible desarrollar dispositivos con las mismas capacidades y precios más económicos? ¿Cómo puedo fabricar mis nodos sensores de bajo coste?

Esta tesis responde a estas preguntas y muestra algunas de las muchas aplicaciones que los nodos sensores pueden tener. En esta tesis hemos propuesto (e implementado en algunos casos) el desarrollo de nodos sensores para la monitorización del medio, a partir de dispositivos de bajo coste. Para la implementación de un nodo sensor, y en definitiva la red que une a todos estos nodos, es importante conocer el medio donde trabajarán. A lo largo de este documento se presentan las investigaciones llevadas a cabo para el desarrollo de sensores en tres ámbitos de aplicación.

En el primero de ellos, se desarrollan dispositivos multisenores para la monitorización del medio. La aplicación de las redes de sensores inalámbricas al medio natural precisa un estudio de cómo se ven afectadas las señales en función de la distancia, vegetación, humedad del ambiente, etc. Focalizamos nuestros desarrollos en la verificación de incendios en zonas rurales y en el control de plagas en viñedos donde la detección precoz de estos eventos genera elevados ahorros económicos. También proponemos el desarrollo de una red de collares sensores para ganado domestico, que nos ayudará a reducir y prevenir en muchos casos, los ataques de lobos y hurtos de crías. Por último, dentro de este grupo, presentamos una red que permite detectar anomalías de los materiales en edificios y otra red de sensores que permite monitorizar las personas mayores o deficientes que se mueven junto con un grupo en una excursión o actividad.

El segundo grupo de aplicaciones hace referencia a la monitorización de espacios en entornos de interior. Para ello hemos analizado el comportamiento de las señales inalámbricas en diferentes escenarios. Los resultados nos han permitido extraer un nuevo método de diseño de las redes inalámbricas en interiores. Nuestro método permite definir la mejor ubicación de los dispositivos de red y nodos sensores en interiores con un ahorro en el número de sensores del 15%.

Por último, se presenta el estudio sobre las comunicaciones subacuáticas basadas en las ondas electromagnéticas donde analizamos la dependencia de las comunicaciones subacuáticas en agua dulce en función de la frecuencia, temperatura, tasas de transferencia de datos y modulación.

Relacionado con el medio subacuático, presentamos 2 propuestas. La primera de ellas hace referencia a la implementación de una red de sensores para granjas marinas que nos permite reducir la cantidad de residuos depositados en el lecho marino y reducir el porcentaje de comida desperdiciada. La segunda propuesta es el desarrollo de dos sensores oceanográficos que nos

permitirían controlar la cantidad de comida y heces depositadas en el suelo y controlar la turbidez del agua de manera simple y económica

Todos estos desarrollos y propuestas han estado precedidos por un exhaustivo estudio sobre los problemas energéticos que las redes de sensores inalámbricas presentan y las técnicas que pueden emplearse para prolongar la vida útil de la red y mejorar su estabilidad.

Resum

Hi ha molts treballs relacionats amb el disseny i desenvolupament de nodes sensors on es presenten gran varietat d'aplicacions. Les xarxes de sensors sense fils poden facilitar i millorar alguns aspectes de la nostra vida diària. És fàcil, pensar que si aquest tipus de dispositiu és tan beneficiós per a nosaltres i per a l'entorn on vivim, el preu hauria de ser relativament barat. Però podem comprovar que això no és així. ¿Per què aquests dispositius són tan cars? Seria possible desenvolupar dispositius amb les mateixes capacitats i preus més econòmics? Com puc fabricar els meus nodes sensors?

Aquesta tesi respon a aquestes preguntes i mostra algunes de les moltes aplicacions que els nodes sensors poden tenir. En aquesta tesi hem proposat (i implementat en alguns casos) el desenvolupament de nodes sensors per a la monitorització del medi a partir de dispositius de baix cost. Per a la implementació d'un node sensor, i en definitiva la xarxa que uneix a tots aquests nodes, és important conèixer el medi on treballaran. Al llarg d'aquest document es presenten les investigacions dutes a terme per al desenvolupament de sensors en tres àmbits d'aplicació.

En el primer d'ells, es desenvolupen dispositius multisensors per a la monitorització del medi. L'aplicació de les xarxes de sensors sense fils al medi natural necessita un estudi de com es veuen afectades les senyals en funció de la distància, vegetació, humitat de l'ambient, etc. Focalitzem els nostres desenvolupaments en la verificació d'incendis en zones rurals i en el control de plagues en vinyes on la detecció precoç d'aquests esdeveniments genera elevats estalvis econòmics. També proposem el desenvolupament d'una xarxa de collarets sensors per a bestiar domèstic, que ens ajudarà a reduir i previndre en molts casos, els atacs de llops i furts de cries. Finalment, dins d'aquest grup, presentem una xarxa que permet detectar anomalies dels materials en edificis i una altra xarxa de sensors que ens permet monitoritzar les persones grans o deficients, que es mouen juntament amb un grup, en una excursió o activitat.

El segon grup d'aplicacions, fa referència a la monitorització d'espais en entorns d'interior. Per a això hem analitzat el comportament dels senyals sense fils en diferents escenaris. Els resultats ens han permés extraure un nou mètode de disseny de les xarxes sense fils en interiors. El nostre mètode permet definir la millor ubicació dels dispositius de la xarxa i nodes sensors en interiors amb un estalvi, en el nombre de sensors, del 15%.

Finalment, es presenta l'estudi sobre les comunicacions subaquàtiques basades en les ones electromagnètiques on analitzem la dependència de les comunicacions subaquàtiques en aigua dolça en funció de la freqüència, temperatura, taxes de transferència de dades i modulacions.

Relacionat amb el medi subaquàtic, presentem 2 propostes. La primera d'elles fa referència a la implementació d'una xarxa de sensors per a granges marines que ens permet reduir la quantitat de residus dipositats al fons marí i reduir el percentatge de menjar desaprofitat. La segona proposta és el desenvolupament de dos sensors oceanogràfics que ens permetrien controlar la quantitat de

menjar i excrements dipositada a terra i controlar la terbolesa de l'aigua de manera simple i econòmica

Tots aquests desenvolupaments i propostes han estat precedits per un exhaustiu estudi sobre els problemes energètics que les xarxes de sensors sense fils presenten i les tècniques que poden emprar-se per a allargar la vida útil de la xarxa i millorar la seva estabilitat.

Chapter 6

Underwater Wireless Communications based on Electromagnetic Waves

6.1 Introduction

Nowadays, there is an extensive research activity in underwater communications and underwater ad-hoc networks. On one hand, the main research lines are based on increasing the distance and bandwidth, and, on the other hand, the attempt to reduce the energy consumption of underwater devices, with the aim of increasing the network lifetime [157] [344]. Underwater communication research is primarily focused on the use of optical signals, EM signals and the propagation of acoustic and ultrasonic signals. Each technique has its own characteristics, with benefits and drawbacks, mainly due to the chemical characteristics [174] and physical constraints of the medium [114] [115].

Systems based on optical communication are able to reach very high propagation speed. However a strong backscattering is caused by suspended particles and they are affected by the turbidity of the water, so they are not good options for long distances.

Systems based on acoustic waves are not so sensitive to the particles suspended in the water and to the turbidity of the water. Moreover, they are the most used methods, since they are able to reach large distances (over 20 km [133]). Although acoustic communication is a proven technology, it presents some main drawbacks, like the low data rate (0 b/s to 20kb/s), which is limited by some factors, such as low carrier frequency, strong reflections and attenuation when the communication is performed near the surface, as well as poor performance in turbid water, sensitivity to varying environmental characteristics, and the salinity or turbidity of the water. In acoustic and ultrasonic communications, researchers usually work on varying the type of modulation and communication protocol, in order to minimize the effects of reflections, and on achieving a communication data rate as high as possible.

When higher data rates are needed, we should make use of radio frequency (RF) methods, which are able to reach communication data rates of up to 100 Mb/s in very short distances, apart from presenting substantial immunity from the environmental features. EM waves, in the RF range, can also be a good option for underwater wireless communication systems. EM waves are less sensitive to reflection and refraction effects in shallow water than acoustic waves. In addition, suspended particles have very little effect on them. The speed of EM waves is higher than the acoustic ones, (150,000 times greater). The speed of an EM wave mainly depends on permeability (μ), permittivity (ε), conductivity (σ) and volume charge density (ρ) [345]. These parameters change with the type of water and the electrical conductivity value associated with the medium often varies, thus the wave propagation speed and absorption coefficient, which are directly related to the working frequency, also vary. Conductivity presents different values for each case, seawater has a high conductivity average value, which is around 4 S/m (obviously it changes with the salinity and physical properties of sea water), but in fresh water the typical value is 0.01 S/m and drinking water presents a conductivity between 0.005 and 0.05 S/m. Moreover, the permittivity of seawater changes as a function of the frequency, the temperature and the salinity. In [346][347], authors provided a relationship model of this dependency in the water. Thus, the main problem for underwater communications based on EM waves is the high attenuation due to the conductivity of the water. This attenuation increases when the EM wave frequency increases. Hence, the higher frequencies will register greater signal losses.

In this chapter, we present the tests performed at different frequencies and modulations in order to measure several parameters such as minimum depth, distance between devices and signal transmission characteristics. We perform the practical study at 2.4 GHz ISM frequency band, using devices compatible with IEEE 802.11 standard. In order to determine if there is any dependence between the wireless signal behavior and the frequency, data transfer rates or temperature, we will analyze the results of each case by using the analysis of variance (ANOVA).

We are going to use a two-way ANOVA, because we want to determine if the value of maximum distance depends on the data transfer rate and/or the working frequency. Both factors are analyzed separately as Rows (dependence with data transfer rate) and as columns (dependence with working frequency). For all analysis of variance, the significance level α=0.05.

We have analyzed IEEE 802.15.4 standard [6] which also works on this frequency. A priori, we thought that due to the low-power consumption of IEEE 802.15.4, it would be better to use these devices as sensor nodes. However, our application needs data transfer rates higher than the ones offered by IEEE 802.14.5. For this reason, we decided to sacrifice a little power consumption in favor of improved data transfer rates. Table 6.1 shows a comparison of the maximum data transfer rates of both wireless technologies.

Table 6.1. Comparison of different wireless standards.

Standard	Frequency	Data Rate
IEEE 802.11 b	2.4 GHz	11 Mbps
IEEE 802.11 g	2.4 GHz	54 Mbps
IEEE 802.15.4	2.4 GHz	250kbps
IEEE 802.15.4	868/915MHz	40 kbps

These tests are performed in a swimming pool with fresh water. We set up an underwater point-to-point link between two antennae in a waterproof case. We also use two computers connected to each antenna in order to monitor the activity of the underwater point-to-point link. We have used the echo request and echo reply packets in order to perform our tests.

The rest of this chapter is structured as follow. Section 6.2 explains the scenario used in our test bench and the strategies used to take measurements. This section also shows the results of two practical studies in underwater environment. In Section 6.3, we show the best results and comparison with other studies. Finally, we will see the conclusion of this chapter.

6.2 Signal Behavior of EM Waves in Fresh Water

In this section, we show the scenario used to take our measurements. In addition, we explain the equipment and the software used in our tests. Finally, we describe the performed tests and the parameters used to perform our measurements.

We have performed two studies at different temperatures. In first study, we have analyzed the behavior of EM waves for temperatures of 16ºC, 18ºC, 20ºC and 22ºC for all modulations supported by IEEE 802.11 Standard meanwhile in the second study we have only performed the study for BPSK, QPSK and CCK modulations at 26 ºC. The main reason of this division is because the results of OFDM al 26ºC are very bad compared to the ones obtained at the rest of temperatures.

6.2.1 Experimental Setup

For the measurements, we have used a swimming pool with 32 m^2 surface, with a length of 8 meters and 4 meters wide. The swimming pool depth ranges between 1.50 m and 1.80 m. It is built with walls of bricks that are covered with small mosaic tiles. The size of this structure allows us to avoid any reflection on the walls, ground and water surface. In order to perform our measurements, we have used an ad hoc wireless connection between two laptops with two vertical monopole antennae placed inside the water. We used two HP pavilion dv6-6c13ss Intel Core i7 2670QM with 4GB RAM memory and the antennae had 2 dBi gain.

We put each antenna in a sealed plastic box to make it both watertight and airtight. We used a pigtail of 3 m. to connect each antenna with each laptop which was located outside the water. Antennae are placed under the water with enough depth to avoid any transmission to the open air.

Measurements were taken in freshwater. The amount of chlorine and bromine dissolved in the water was fixed to 0.3 mg/l. and pH value was 7.2. Figure 6.1 shows a scheme of the scenario and the location of the devices inside the swimming pool.

In order to determine the minimum depth to ensure that the taken measures are valid and the signal does not spread out of the water, we have done the following process. We established an ad hoc wireless connection between both antennae outside the water. After that, we introduced one antenna progressively inside the water and checked it every 5 cm. We stopped when we did not detect any signal with the antenna placed outside the water from the antenna located inside the water. We placed the antennae at 30 cm. Then, we used that distance to make our tests. This test demonstrates that this depth is enough to ensure that the only signal received by the laptop is provided by the antenna placed inside the water.

In order to take the measurements, we have used a MS-DOS shell command that let us check the status of the network connection. Concretely we used the ping command which provides the round trip time (RTT) for each packet (see Figure 6.2).

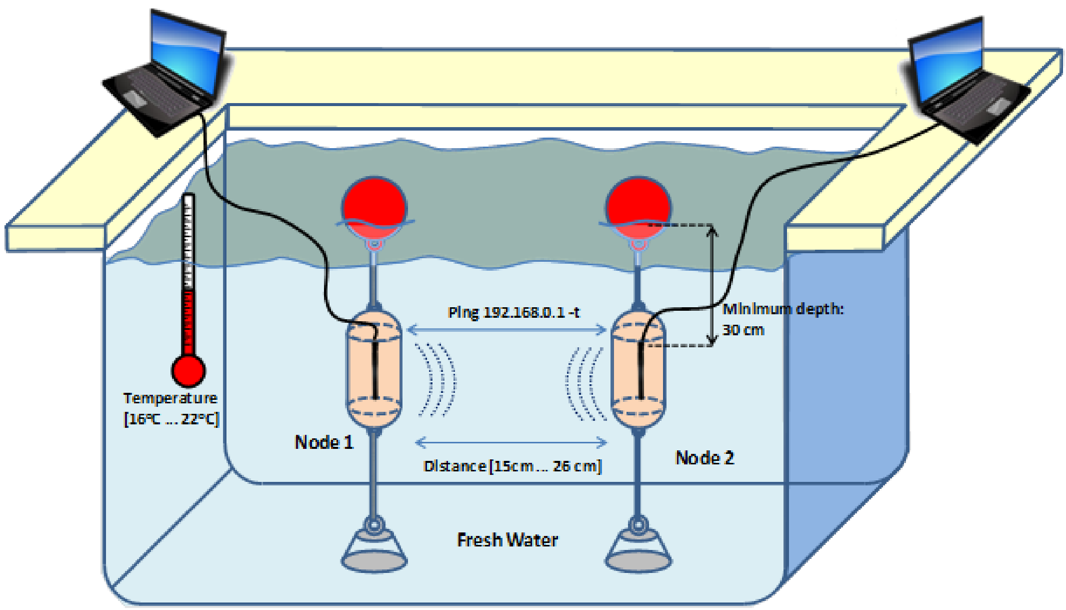

Figure 6.1. Swimming pool where measures have been taken

In our tests, we have analyzed the RTT between both devices as a function of the distance between them. We have also measured this parameter for different types of modulations and frequencies. RTT average has been estimated taking into account only the packets that performed the round-trip successfully. When a packet was not received or was received wrong, we assigned the value of 3,000 ms but this value was not taken into account in the RTT average estimation. We have used a threshold value of 3,000 ms, because it is commonly used [348].

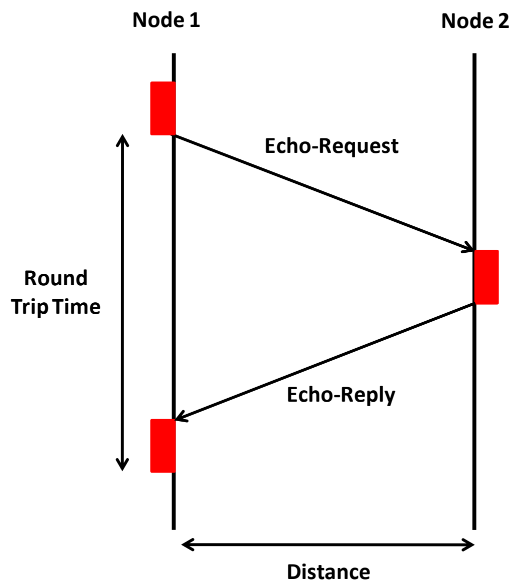

Figure 6.2. Packet flow diagram

Tests have performed at 2.4 GHz frequency band, specified in the IEEE 802.11b/g standard (range between 2,412 MHz and 2,462 MHz). The modulation used in our test were BPSK at 1 Mbps, QPSK at 2 Mbps, CCK at 5.5 Mbps and 11 Mbps, and finally OFDM at 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 22 Mbps, 24 Mbps, 36 Mbps, 48 Mbps, 54 Mbps.

We have performed all these tests for the temperatures of 16°C, 18°C, 20°C, 22°C and 26°C.

Table 6.2. Modulations of IEEE 802.11b/g standard used in our tests.

<table>
<tr><th>Modulation or scheme</th><th>Data transfer rate</th><th>Modulation or scheme</th><th colspan="2">Data transfer rate</th></tr>
<tr><td>BPSK</td><td>1Mbps</td><td rowspan="5">OFDM</td><td>6Mbps</td><td>9Mbps</td></tr>
<tr><td>QPSK</td><td>2Mbps</td><td>12Mbps</td><td>18Mbps</td></tr>
<tr><td rowspan="3">CCK</td><td>5.5Mbps</td><td>22Mbps</td><td>24Mbps</td></tr>
<tr><td rowspan="2">11Mbps</td><td>36Mbps</td><td>48Mbps</td></tr>
<tr><td colspan="2">54Mbps</td></tr>
</table>

Finally, the maximum distance will be determined as the distance between antennae where the number of delivered packets without errors is higher than 50 % at least. Each test has duration of 3 minutes. The average value of RTT for each case and its typical error are calculate with a minimum of 150 samples.

6.2.2 First study: Measurements at 16 °C, 18 °C, 20 °C and 22 °C

This section shows the obtained results. Each subsection represents the maximum distance between the two antennae and the average RTT value for these distances as a function of the working frequency. The results are analyzed for each one of the defined temperatures in our tests.

6.2.2.1. Measurements for 16 °C

At 16 °C, we performed the test for the frequencies between 2,412 MHz and 2,452 MHz. For higher frequency values, in this temperature, it was not possible to establish an underwater wireless link. Figure 6.3 shows the maximum distances for each data transfer rate as a function of the working frequency at 16 °C.

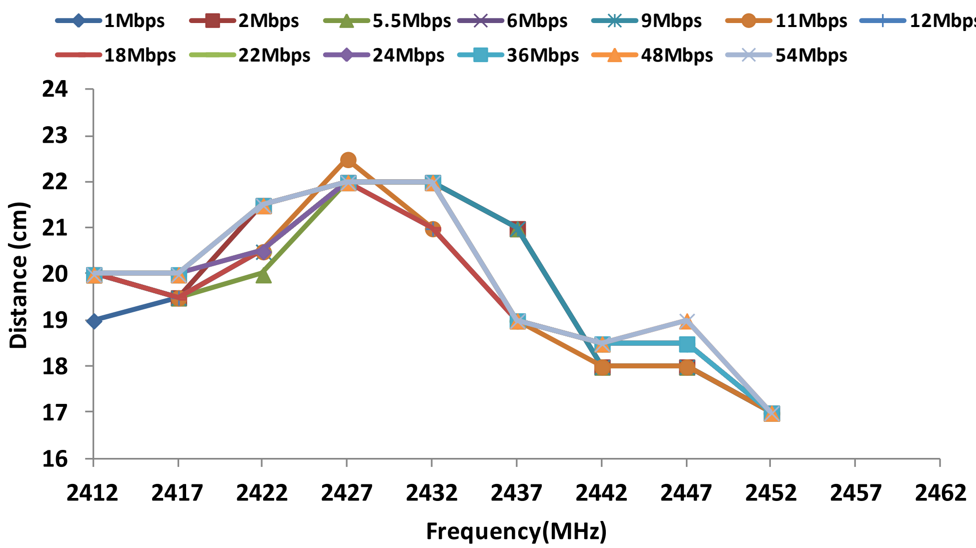

Figure 6.3. Maximum distances for data transfer rates at 16°C.

The first significant feature is that all data transfer rates have similar behaviors. We can see that the greater distances for all data transfer rates are observed between the frequencies 2,427 MHz and 2,432 MHz. The data transfer rate that shows greater distance (22.5 cm) is 11Mbps, which uses CCK modulation scheme. However the data transfer rate of 1 Mbps (which uses the BPSK modulation) and 2 Mbps (which uses QPSK modulation) maintains distances between 21.5 and 22 cm in the frequency range between 2,422 MHz and 2,432 MHz. Table 6.3 shows a summary of the statistical results for measurements at 16 °C.

- Description of groups to be compared: Each Frequency and each data transfer rate at 16°C
- Variable to be studied: maximum distance between antennae at 16°C.

As Table 6.3 shows, the average value of each group (columns) is numerically distinct. We can focus our analysis on the dependence of maximum distance with working frequency and data transfer rate. Average values of rows seem to be very similar. This leads us to think that the variation in data transfer rates for a same frequency is not significant.

Table 6.4 shows the analysis of variance measurements at 16 °C.

Table 6.3. Sumary of statistical results for measurements at 16 °C

Summary	Nº of data	Sum	Average	Variance
Row 1	9	178	19.7777778	3.63194444
Row 2	9	179	19.8888889	3.54861111
Row 3	9	177.5	19.7222222	3.19444444
Row 4	9	178	19.7777778	3.25694444
Row 5	9	178	19.7777778	3.25694444
Row 6	9	175.5	19.5	2.9375
Row 7	9	176	19.5555556	2.27777778
Row 8	9	176	19.5555556	2.27777778
Row 9	9	177.5	19.7222222	2.75694444
Row 10	9	177.5	19.7222222	2.75694444
Row 11	9	178.5	19.8333333	3.0625
Row 12	9	179	19.8888889	2.92361111
Row 13	9	179	19.8888889	2.92361111
Column1	13	259	19.9230769	0.07692308
Column2	13	256	19.6923077	0.06410256
Column3	13	271	20.8461538	0.30769231
Column4	13	286.5	22.0384615	0.01923077
Column5	13	283	21.7692308	0.19230769
Column6	13	257	19.7692308	1.02564103
Column7	13	237.5	18.2692308	0.06730769
Column8	13	238.5	18.3461538	0.14102564
Column9	13	221	17	0

Table 6.4. ANOVA for measurements at 16 °C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	1.85470085	12	0.1545584	0.71074719	0.7375945	1.85440887
Columns	289.568376	8	36.196047	166.449949	9.0723E-53	2.03631902
Error	20.8760684	96	0.21745905			
Total	312.299145	116				

Analysis of Rows:

We formulate two hypotheses:

- H0 = maximum distance does not depend on the data transfer rate (null hypothesis)
- H1 = maximum distance depends on the data transfer rate (alternative hypothesis)

We see that in the case of rows, the probability value (0.7375945) is higher than the one defined for α. Therefore, the variation of results is not significant. On the other hand, the value of F (0.710) is lower than the critical value of F (1.85). For this reason, we discard the alternative hypothesis and take the null hypothesis. This means that the maximum distance for each frequency does not depend on the data transfer rate. The results do not show significant difference between groups (rows) due to variations in data transfer rates.

Analysis of Columns:

We formulate two hypotheses:

- H0 = maximum distance does not depend on the working frequency (null hypothesis).
- H1 = maximum distance depends on the working frequency (alternative hypothesis).

We see that in case of the columns, the value of the probability ($9.0723*10^{-53}$) is lower than defined for α. Therefore, the variation of the results is significant. Moreover, the value of F (166.44) is greater than the critical value of F (2.036). We can discard the null hypotheses for taking the alternative which means that the maximum distance between antennae at 16 ªC depends on the working frequency. There is a significant difference between groups (columns) which is due to the increase in the working frequency and not due to the random effect.

With this, we have checked that the maximum distance values are statistically different and they depend on the working frequency significantly. In addition, the effect of data transfer rate and consequently the modulations, is not significant to obtain the maximum distance.

Table 6.5 shows the RTT values and their typical errors in ms for maximum distances of each data transfer rate depending on the working frequency to the temperature of 16 °C. Numbers in red indicate the best values of RTT in ms., for each data transfer rate. We can see that increasing the distance between antennas does not mean higher RTT values. We observe that the data transfer rate of 11 Mbps, operating at the frequency of 2,427 MHz, has a RTT value of 4.85 ms. This is the most efficient combination of settings for this temperature.

6.2.2.2. Measurements for 18 °C

We took measurements for frequencies between 2,412 MHz and 2,452 MHz at 18ºC. It was not possible to establish an underwater wireless link for higher frequency in this temperature. Figure 6.4 shows the maximum distance for each data transfer rate depending on the frequency, for a temperature of 18 °C.

Under these conditions of temperature, we observe that the maximum distance achieved was 22.5 cm., for 2,437 MHz. The data transfer rate that reached this distance was 11Mbps (which uses the CCK modulation scheme), 12 Mbps and 18 Mbps (using OFDM). The data transfer rates of 22 Mbps, 24 Mbps, 36 Mbps, 48 Mbps and 54 Mbps (using OFDM modulation) reached the maximum distance of 21.5 cm at the frequency of 2,417 MHz. The rest of data transfer rates present maximum distances lower than 21 cm.Table 6.6 shows a summary of the statistical results for measurements at 18 °C.

Table 6.5. Values of RTT in ms for 16°C

Data Transfer Rates	Frequency (MHz) 2,412	2,417	2,422	2,427	2,432	2,437	2,442	2,447	2,452	2,457	2,462
1 Mbps	5.22 ± 0.24	3.29 ±0.06	3.98 ± 0.21	3.53 ± 0.34	**3.12 ± 0.05**	2.21 ±0.05	3.00 ± 0.00	3.22 ± 0.06	3.19 ± 0.03	X	X
2 Mbps	6.75 ± 0.46	3.02 ± 0.07	5.75 ± 0.21	2.74 ± 0.08	**6.27 ± 1.57**	2.95 ± 0.06	2.13 ± 0.03	3.66 ± 0.11	4.08 ± 0.46	X	X
5.5 Mbps	11.64 ± 0.75	2.02 ± 0.11	2.56 ±0.11	**3.29 ± 0.15**	3.57 ± 0.14	4.41 ± 0.12	1.18 ± 0.03	4.44 ± 0.12	3.93 ± 0.11	X	X
6 Mbps	15.47 ± 0.96	4.12 ± 0.12	4.37 ± 0.12	**4.28 ± 0.11**	5.25 ± 0.11	7.08 ±0.12	1.08 ± 0.02	4.87 ± 0.14	5.75 ± 0.14	X	X
9 Mbps	18.65 ± 1.39	4.94 ± 0.12	5.06 ± 0.10	**5.07 ± 0.11**	6.25 ±0.23	8.43 ± 0.13	1.11 ± 0.04	7.66 ± 0.26	6.12 ± 0.10	X	X
11 Mbps	41.07 ± 4.38	5.27 ± 0.12	5.59 ± 0.36	**4.85 ± 0.15**	3.51 ± 0.29	3.59 ± 0.11	1.58 ± 0.04	9.44 ± 0.20	6.26 ± 0.40	X	X
12 Mbps	22.56 ± 2.04	6.43 ± 0.14	6.95 ± 0.13	**6.45 ± 0.14**	5.00 ± 0.07	7.27 ± 0.19	1.20 ± 0.06	5.37 ± 0.22	8.09 ± 0.36	X	X
18 Mbps	5.34 ± 0.20	3.25 ± 0.10	4.03 ± 0.10	**8.21 ± 0.40**	40.90 ± 2.93	3.64 ± 0.12	1.25 ± 0.03	5.36 ± 0.22	5.13 ±0.11	X	X
22 Mbps	11.16 ± 0.39	14.97 ± 0.51	6.00 ± 0.59	**22.49 ± 3.36**	39.17 ± 1.42	20.99 ± 1.94	1.58 ± 0.04	5.07 ± 0.13	5.48 ± 0.14	X	X
24 Mbps	6.69 ± 0.14	7.33 ± 0.23	5.17 ± 0.13	**15.16 ± 2.74**	56.23 ± 5.34	4.53 ± 0.09	1.49 ± 0.04	4.68 ± 0.11	7.49 ± 0.15	X	X
36 Mbps	8.95 ± 0.17	9.59 ± 0.27	7.81 ± 0.19	**8.04 ± 0.49**	77.92 ± 2.47	6.08 ± 0.17	2.13 ± 0.03	5.11 ± 0.11	10.44 ± 0.34	X	X
48 Mbps	8.81 ± 0.17	9.05 ± 0.29	9.45 ± 0.22	**9.07 ± 1.39**	126.72 ± 39.68	6.23 ± 0.16	2.61 ± 0.04	6.46 ± 0.16	10.29 ± 0.22	X	X
54 Mbps	9.03 ± 0.18	8.87 ± 0.26	9.67 ± 0.23	7.51 ± 0.18	**9.35 ± 0.23**	7.04 ± 0.13	3.20 ± 0.05	15.83 ± 3.24	10.73 ± 0.33	X	X

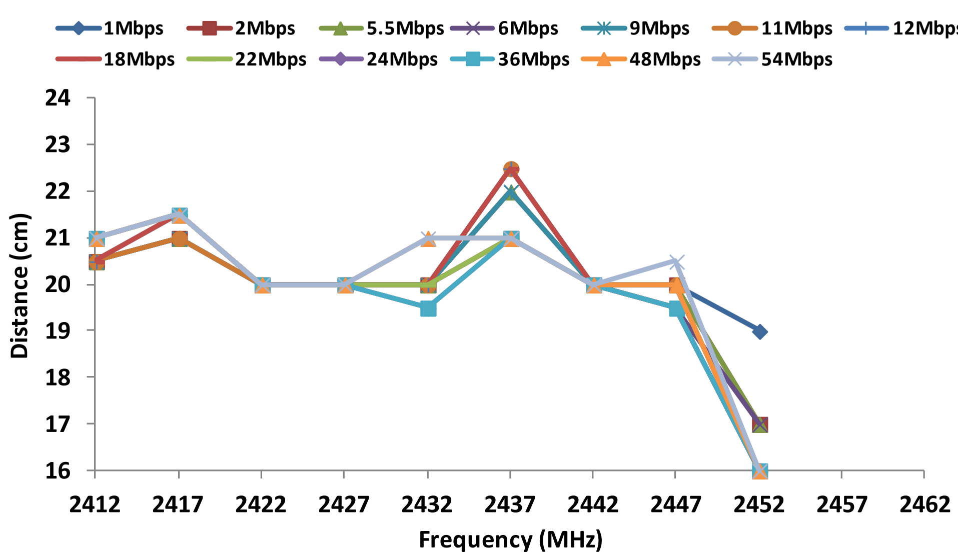

Figure 6.4. Maximum distances for data transfer rates at 18°C.

Table 6.6. Summary of statistical results for measurements at 18 °C

Summary	Nº of data	Sum	Average	Variance
Row 1	9	181.5	20.1666667	0.375
Row 2	9	179.5	19.9444444	1.40277778
Row 3	9	180.5	20.0555556	1.77777778
Row 4	9	180	20	1.8125
Row 5	9	179	19.8888889	2.67361111
Row 6	9	180	20	2.9375
Row 7	9	180.5	20.0555556	3.09027778
Row 8	9	180	20	3.125
Row 9	9	179	19.8888889	2.54861111
Row 10	9	178.5	19.8333333	2.5625
Row 11	9	178.5	19.8333333	2.5625
Row 12	9	180.5	20.0555556	2.65277778
Row 13	9	181	20.1111111	2.67361111
Column1	13	269	20.6923077	0.06410256
Column2	13	276.5	21.2692308	0.06730769
Column3	13	260	20	0
Column4	13	260	20	0
Column5	13	261	20.0769231	0.20192308
Column6	13	280.5	21.5769231	0.45192308
Column7	13	260	20	0
Column8	13	257.5	19.8076923	0.10576923
Column9	13	214	16.4615385	0.76923077

- Description of groups to be compared: Each Frequency and each data transfer rate at 18°C
- Variable to be studied: maximum distance between antennae at 18°C.

As Table 6.6 shows, the average value of each group (columns) is numerically distinct. We can focus our analysis on the dependence of maximum distance with working frequency and data transfer rate. Average values of rows seem to be very similar. This leads us to think that the variation in data transfer rates for a same frequency is not significant.

Table 6.7 shows the analysis of variance measurements at 18 °C.

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant.

Table 6.8 shows the RTT values and their typical errors in ms. of the maximum distances for all data transfer rates as a function of the working frequency at 18 °C. Numbers in red indicate the best RTT values in ms., for each data transfer rate. Looking at the three data transfer rates which reach the maximum distances (11 Mbps, 12 Mbps and 18 Mbps) we can see that the data rate that provides lowest RTT was 18 Mbps, with a value of 5.61 ms.

Table 6.7. ANOVA for measurements at 18 °C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	1.17521368	12	0.09793447	0.50148165	0.90909075	1.85440887
Columns	222.807692	8	27.8509615	142.613175	8.5592E-50	2.03631902
Error	18.7478632	96	0.19529024			
Total	242.730769	116				

Table 6.8.. Values of RTT in ms for 18°C

	Frequency (MHz)										
Data Transfer Rates	**2412**	**2417**	**2422**	**2427**	**2432**	**2437**	**2442**	**2447**	**2452**	**2457**	**2462**
1 Mbps	3.14 ± 0.03	**4.19 ± 0.12**	3.08 ± 0.03	4.86 ± 0.24	5.01 ± 0.31	**3.30 ± 0.05**	5.29 ± 1.69	3.31 ± 0.09	24.42 ± 2.04	X	X
2 Mbps	2.58 ± 0.05	**4.01 ± 0.32**	2.86 ± 0.08	8.91 ± 0.55	8.40 ± 0.50	**4.50 ± 0.12**	3.72 ± 0.11	2.70 ± 0.08	22.17 ± 2.37	X	X
5.5 Mbps	2.58 ± 0.07	3.73 ± 0.24	2.47 ± 0.09	14.16 ± 0.73	14.32 ± 0.83	**10.65 ± 0.34**	7.78 ± 0.42	4.87 ± 0.35	84.071 ± 4.21	X	X
6 Mbps	3.63 ± 0.06	6.69 ± 0.25	4.78 ± 0.15	10.39 ± 0.18	9.71 ± 0.13	**8.24 ± 0.20**	10.14 ± 0.32	3.22 ± 0.06	1.00 ± 0.00	X	X
9 Mbps	4.43 ± 0.08	7.93 ± 0.31	12.38 ± 0.64	11.24 ± 0.17	10.49 ± 0.13	**10.39 ± 0.15**	10.21 ± 0.31	4.11 ± 0.07	1.00 ± 0.00	X	X
11 Mbps	3.60 ± 0.09	6.54 ± 0.43	24.74 ± 4.97	21.56 ± 1.04	17.25 ± 0.56	**14.57 ± 0.41**	8.27 ± 0.22	11.26 ± 3.23	1.00 ± 0.00	X	X
12 Mbps	5.57 ± 0.09	11.48 ± 1.33	21.46 ± 1.23	11.61 ± 0.27	12.85 ± 0.16	**13.14 ± 0.74**	10.75 ± 0.13	8.71 ± 1.23	1.00 ± 0.00	X	X
18 Mbps	2.84 ± 0.05	4.82 ± 0.08	3.68 ± 0.08	5.16 ± 0.14	7.20 ± 0.16	**5.61 ± 0.24**	6.094 ± 0.22	7.21 ± 0.23	1.00 ± 0.00	X	X
22 Mbps	14.56 ± 0.94	**11.21 ± 0.28**	10.84 ± 0.81	16.60 ± 1.47	19.40 ± 0.94	11.57 ± 0.19	9.83 ± 0.34	7.07 ± 0.36	1.00 ± 0.00	X	X
24 Mbps	7.53 ± 0.24	**5.77 ± 0.11**	9.94 ± 0.14	6.76 ± 0.156	8.21 ± 0.13	7.53 ± 0.11	7.71 ± 0.10	6.58 ± 0.16	1.00 ± 0.00	X	X
36 Mbps	8.54 ± 0.20	**7.64 ± 0.18**	9.54 ± 0.20	9.06 ± 0.19	11.01 ± 0.21	10.00 ± 0.17	9.75 ± 0.14	7.97 ± 0.175	1.00 ± 0.00	X	X
48 Mbps	8.62 ± 0.18	**7.49 ± 0.15**	9.35 ± 0.12	9.02 ± 0.17	10.39 ± 0.20	7.74 ± 0.16	6.81 ± 0.71	15.23 ± 2.31	1.00 ± 0.00	X	X
54 Mbps	8.93 ± 0.21	**8.25 ± 1.20**	10.03 ± 0.62	9.31 ± 0.30	9.67 ± 1.86	7.00 ± 0.13	8.06 ± 0.20	7.98 ± 0.17	1.00 ± 0.00	X	X

The best combination of parameters at 18 °C is to work at 2,437 MHz, with 18Mbps data transfer rate (which is used OFDM modulation).

6.2.2.3. Measurements for 20 °C

We were able to establish an underwater link for frequencies between 2,457 MHz and 2,462 MHz at 20 °C. Figure 6.5 shows the maximum distances for each data transfer rate as a function of the working frequency at 20 °C.

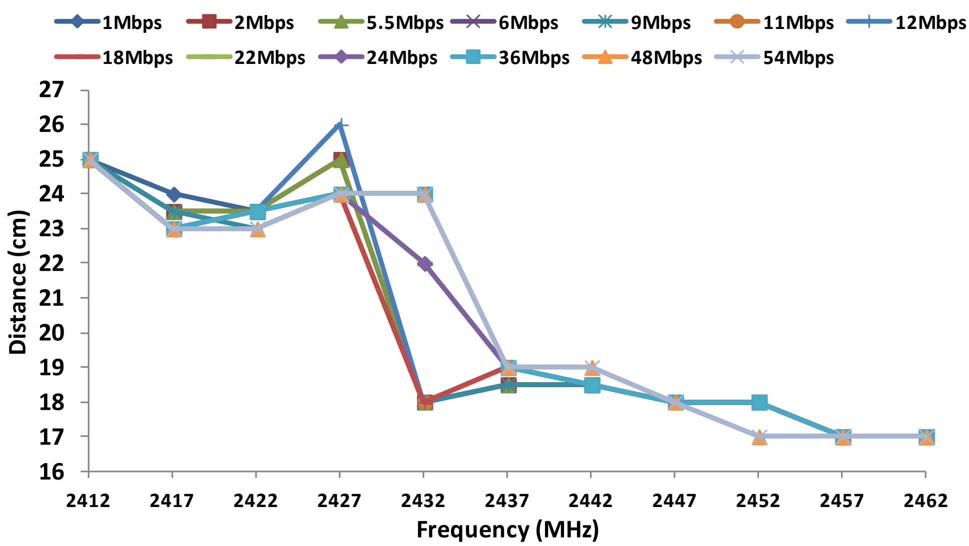

Figure 6.5. Maximum distances for data transfer rates at 20°C.

As we can see, all data transfer rates have two frequencies which have greater distances between antennas. For 2,412 MHz, all data transfer rates reach a distance of 25 cm. The following frequency to highlight is 2,427 MHz where the data transfer rate of 12 Mbps reaches a maximum distance of 26 cm. For the same frequency, data rates of 1 Mbps, 2 Mbps and 5.5 Mbps reached distances of 25 cm. The other data transfer rates are kept below 24cm. We can also note that 36 Mbps, 48 Mbps and 54 Mbps present their maximum distances at the frequency of 2,432 MHz (24 cm), while the remaining data transfer rates (except for 12Mbps) offer very low distances (18cm). Table 6.9 shows a summary of the statistical results for measurements at 20 °C. In this case, the parameters to be analyzed are:

- Description of groups to be compared: Each Frequency and each data transfer rate at 20°C
- Variable to be studied: maximum distance between antennae at 20°C.

As Table 6.9 shows, the average value of each group (columns) is numerically distinct. We can focus our analysis on the dependence of maximum distance with working frequency and data transfer rate. Average values of rows seem to be very similar. This leads us to think that the variation in data transfer rates for a same frequency is not significant.

Table 6.10 shows the analysis of variance measurements at 20 °C.

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant.

Table 6.11 shows the RTT values in ms. for the maximum distances for all data transfer rates as a function of working frequency at 20 °C. Numbers in red indicate the best RTT values in ms., for each data transfer rate. On the one hand we can see that 12 Mbps has a RTT value of 26.21 ms for distances of 26 cm. Moreover, we see that data rates of 1 Mbps, 2 Mbps and 5.5 Mbps record RTT values below 9 ms for 2,412 MHz, while for 2,427 MHz, their values are above 22 ms. Both frequencies reach the same distances.

Table 6.9. Summary of statistical results for measurements at 20 °C.

Summary	Nº of data	Sum	Average	Variance
Row 1	11	222.5	20.2272727	11.2181818
Row 2	11	222	20.1818182	10.8636364
Row 3	11	222	20.1818182	10.8636364
Row 4	11	220.5	20.0454545	9.67272727
Row 5	11	220.5	20.0454545	9.67272727
Row 6	11	221	20.0909091	9.54090909
Row 7	11	223	20.2727273	11.4681818
Row 8	11	221	20.0909091	9.54090909
Row 9	11	225	20.4545455	9.32272727
Row 10	11	225	20.4545455	9.32272727
Row 11	11	227	20.6363636	10.3045455
Row 12	11	226	20.5454545	10.4727273
Row 13	11	226	20.5454545	10.4727273
Column1	13	325	25	0
Column2	13	301.5	23.1923077	0.10576923
Column3	13	304	23.3846154	0.04807692
Column4	13	317	24.3846154	0.42307692
Column5	13	260	20	7.33333333
Column6	13	244.5	18.8076923	0.06410256
Column7	13	241.5	18.5769231	0.03525641
Column8	13	234	18	0
Column9	13	232	17.8461538	0.14102564
Column10	13	221	17	0
Column11	13	221	17	0

Table 6.10. ANOVA for measurements at 20 °C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	5.84265734	12	0.48688811	0.6353129	0.808496131	1.83369528
Columns	1235.3986	10	123.53986	161.200213	1.31338E-64	1.91046106
Error	91.965035	120	0.76637529			
Total	1333.20629	142				

Table 6.11. Values of RTT in ms for 20°C

	Frequency (MHz)										
Data Transfer Rates	**2412**	**2417**	**2422**	**2427**	**2432**	**2437**	**2442**	**2447**	**2452**	**2457**	**2462**
1 Mbps	**4.77 ±0.37**	5.90 ± 0.35	3.05 ± 0.02	**22.87 ±2.52**	3.99 ±0.34	5.58 ±0.56	3.47 ±.07	28.39 ±3.01	4.00 ±0.97	3.00 ±0.02	3.12 ±0.04
2 Mbps	**8.80 ±0.54**	4.05 ± 0.11	55.38 ±9.69	**30.41 ±4.64**	6.45 ±0.41	4.60 ±0.19	5.57 ±0.10	20.73 ±1.78	3.73 ±0.09	2.08 ±0.03	2.28 ±0.08
5.5 Mbps	**3.71 ±1.43**	5.70 ± 0.16	17.08 ± 1.52	**66.61 ±20.26**	9.10 ±0.38	5.53 ±0.22	8.57 ±0.18	20.56 ±4.65	6.22 ±0.78	1.77 ±0.06	2.09 ±0.13
6 Mbps	**3.17 ±0.06**	9.10 ± 0.13	20.10 ± 1.44	17.65 ±3.32	9.39 ±0.13	8.16 ±0.12	8.71 ±0.09	21.88 ±4.31	6.19 ±0.13	1.07 ±0.03	1.44 ±0.09
9 Mbps	**4.01 ±0.06**	10.05 ± 0.13	18.91 ± 1.14	42.31 ±30.78	10.16 ±0.17	8.36 ±0.15	9.51 ±0.10	17.27 ±1.09	7.07 ±0.15	1.86 ±0.08	1.21 ±0.06
11 Mbps	**3.47 ± 0.07**	15.00 ± 0.61	22.44 ±1.65	27.00 ±30.87	14.00 ± 0.49	6.77 ±0.17	12.23 ±0.22	20.77 ±1.87	8.23 ±0.30	1.84 ±0.04	2.03 ±0.08
12 Mbps	5.35 ± 0.08	11.37 ± 0.11	16.02 ±0.80	**26.21 ±3.64**	14.68 ± 2.47	8.49 ±0.16	12.23 ±0.32	18.57 ±1.09	4.32 ±0.10	1.14 ±0.06	1.10 ±0.05
18 Mbps	**4.10 ± 0.14**	5.94 ± 0.11	3.76 ±0.14	5.85 ±0.16	7.26 ±0.14	4.58 ±0.08	5.74 ±0.08	9.75 ±5.5	4.32 ±0.10	1.05 ±0.01	1.30 ±0.09
22 Mbps	**3.46 ± 0.07**	15.35 ± 0.61	4.98 ±0.13	18.22 ±0.92	33.85 ±0.84	8.08 ±0.28	9.94 ±0.26	4.94 ±0.16	7.74 ±0.30	1.99 ±0.08	1.96 ±0.10
24 Mbps	**5.03 ± 0.14**	7.38 ± 0.14	4.68 ±0.17	33.72 ±7.82	4.71 ±0.11	5.76 ±0.11	6.50 ±0.11	5.06 ±0.15	5.29 ±0.13	1.22 ±0.07	1.26 ±0.06
36 Mbps	**6.25 ± 0.21**	9.36 ± 0.24	5.45 ±0.12	10.66 ±0.26	11.34 ±0.49	8.00 ±0.15	8.77 ±0.17	6.04 ±0.14	6.39 ±0.17	1.60 ±0.11	1.47 ±0.07
48 Mbps	**6.03 ± 0.17**	9.86 ± 0.34	6.07 ±0.28	9.66 ±0.24	7.74 ±0.20	8.57 ±0.18	10.37 ±0.26	6.21 ±0.17	6.15 ±0.18	2.56 ±0.11	2.34 ±0.06
54 Mbps	**7.32 ± 0.22**	9.98 ± 1.27	6.90 ±0.22	9.58 ± 0.32	7.82 ±0.17	8.63 ±0.16	9.70 ±0.17	7.12 ±0.14	6.93 ±0.16	2.64 ±0.06	2.93 ±0.06

6.2.2.4. Measurements for 22 °C

The highest frequency that allows establishing an underwater wireless link at 22 °C is 2,452 MHz.

Figure 6.6 shows the maximum distances for all data transfer rates depending on the working frequency.

These measures have been carried out at 22 degrees. Similar to the signals behavior to at 18 °C, we can observe that two frequencies at 22 °C showed greater distances.

Firstly, we note that at 2,412 MHz, all data transfer rates can achieve a distance between antennae of 26 cm. At 2,437MHz we observed the second longest distance for all data transfer rates, with the exception of 1 Mbps and 48 Mbps. The maximum distance between antennae was 25 cm. Table 6.12 shows a summary of the statistical results for measurements at 22 °C.

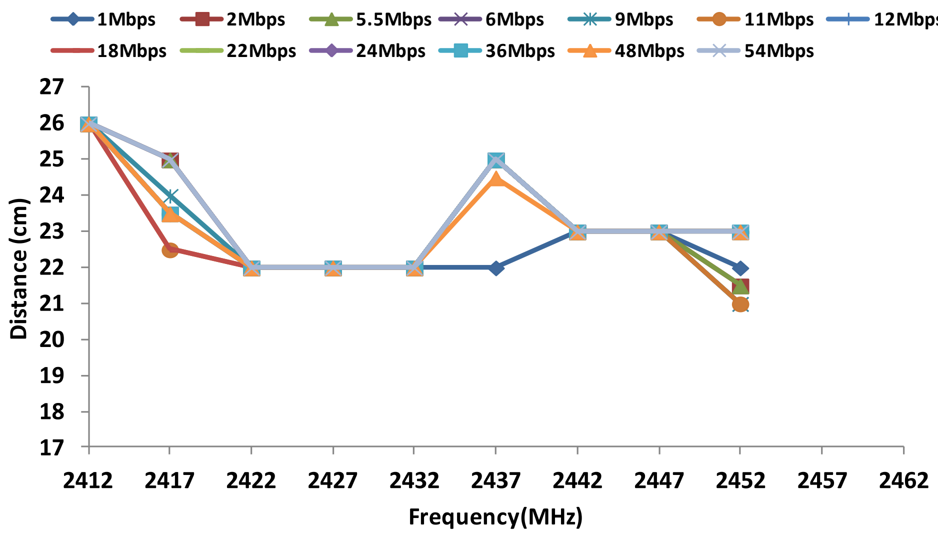

Figure 6.6. Maximum distances for data transfer rates at 22°C.

Table 6.12. Summary of statistical results for measurements at 22 °C.

Summary	Nº of data	Sum	Average	Variance
Row 1	9	207	23	2.25
Row 2	9	209.5	23.2777778	2.69444444
Row 3	9	209.5	23.2777778	2.69444444
Row 4	9	209	23.2222222	2.94444444
Row 5	9	208	23.1111111	2.61111111
Row 6	9	206.5	22.9444444	2.52777778
Row 7	9	209.5	23.2777778	1.94444444
Row 8	9	208.5	23.1666667	2
Row 9	9	209.5	23.2777778	1.94444444
Row 10	9	209.5	23.2777778	1.94444444
Row 11	9	209.5	23.2777778	1.94444444
Column1	13	338	26	0
Column2	13	311.5	23.9615385	0.89423077
Column3	13	286	22	0
Column4	13	286	22	0
Column5	13	286	22	0
Column6	13	321.5	24.7307692	0.69230769
Column7	13	299	23	0
Column8	13	299	23	0
Column9	13	289	22.2307692	0.81730769
Column10	9	207	23	2.25
Column11	9	209.5	23.2777778	2.69444444

- Description of groups to be compared: Each Frequency and each data transfer rate at 22°C
- Variable to be studied: maximum distance between antennae at 20°C.

As Table 6.12 shows, the average value of each group (columns) is numerically distinct. We can focus our analysis on the dependence of maximum distance with working frequency and data transfer rate. Average values of rows seem to be very similar. This leads us to think that the variation in data transfer rates for a same frequency is not significant.

Table 6.13 shows the analysis of variance measurements at 22 °C.

Table 6.13. ANOVA for measurements at 22 °C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	1.88034188	12	0.15669516	0.55784469	0.87039698	1.85440887
Columns	209.311966	8	26.1639957	93.1454834	8.2962E-42	2.03631902
Error	26.965812	96	0.28089387			
Total	238.15812	116				

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant. Table 6.14 shows the RTT values and their typical errors in ms of the maximum distances for all data transfer rates as a function of working frequency at 22 °C. Numbers in red indicate the best values of RTT in ms., for each data transfer rate. As Figure 5 shows all data transfer rates record their greatest distance in the lowest frequency. However, we observed significant changes in RTT values. Firstly, 1 Mbps and 2 Mbps present the lowest values (about 4.75 ms). Furthermore, the data rate of 22 Mbps has a RTT values above 16.50 ms, which is the highest value. At 22° C, the best combination of parameters is selecting 2,412 MHz with data transfer rates of 1 Mbps and 2 Mbps.

6.2.3 Second Study: Performance Results at 26 °C

This section shows the obtained results in the second test. Each subsection represents the maximum distance between the two antennae and the average RTT value for these distances as a function of the working frequency. The results are analyzed for 26ºC. In this case, the modulations used are BPSK at 1 Mbps, QPSK at 2 Mbps, CCK at 5.5 Mbps and 11 Mbps.

6.2.3.1 Performance of BPSK modulation and analytical study for 1Mbps data transfer rate.

Figure 6.7 shows the average RTT in milliseconds for 1 Mbps data transfer rate, when the BPSK modulation is used, as a function of the working frequency and the distance between the wireless sensor nodes. We observe that the highest variations occur between 15 cm and 18 cm. The RTT value for 15 cm is close to 3 ms, while the communication is lost for 18 cm. The average RTT value for distances between 15 cm and 18 cm (at 2,412 MHz, 2,417 MHz, 2,422 MHz, 2,427 MHz and 2,432 MHz) is relatively small, around 20 ms. But at 2,437 MHz the RTT value for 16 cm increases up to 500 ms, while for 17 cm there are not registered packets.

Table 6.14. Values of RTT in ms for 22°C

Data Transfer Rates	Frequency (MHz) 2412	2417	2422	2427	2432	2437	2442	2447	2452	2457	2462
1 Mbps	**4.89 ±0.35**	20.12 ±4.22	3.01 ±0.01	3.21 ±0.2	3.03 ±0.05	3.13 ±0.12	3.03 ±0.01	3.05 ±0.03	3.83 ±0.26	X	X
2 Mbps	**4.73 ±0.17**	13.66 ±2.77	2.17 ±0.03	2.88 ±0.37	2.19 ±0.03	2.19 ±0.04	3.01 ±0.24	9.73 ±0.33	12.00 ±4.06	X	X
5.5 Mbps	**6.86 ±0.31**	18.35 ±2.99	1.17 ±0.04	1.82 ±0.10	1.93 ±0.08	1.10 ±0.03	4.22 ±0.10	5.55 ±0.21	8.82 ±2.20	X	X
6 Mbps	**8.00 ±0.43**	34.58 ± 6.26	5.79 ±0.41	42.63 ±0.83	8.53 ±1.21	7.24 ±0.11	6.26 ±0.14	7.41 ±0.12	4.92 ±0.31	X	X
9 Mbps	**9.31 ±0.40**	20.11 ± 1.90	6.29 ±0.31	6.84 ±0.34	10.19 ±1.01	7.89 ±0.15	7.04 ±0.14	7.41 ±0.12	7.96 ±0.40	X	X
11 Mbps	**14.72 ±0.83**	7.87 ±0.35	3.33 ±0.08	4.93 ±0.34	4.29 ±0.10	2.47 ±0.05	7.83 ±0.50	9.84 ±0.91	14.76 ± 2.64	X	X
12 Mbps	**11.75 ±0.30**	13.15 ±0.72	9.17 ±0.21	7.99 ±0.35	14.42 ±1.27	9.51 ±0.18	8.38 ±0.16	10.68 ±0.39	4.21 ±0.14	X	X
18 Mbps	**10.38 ± 2.16**	3.48 ±0.07	5.53 ±0.52	4.24 ±0.12	3.97 ±0.35	9.53 ±0.11	4.94 ±0.10	5.96 ±0.09	3.85 ±0.27	X	X
22 Mbps	**16.51 ±1.60**	10.93 ±0.83	8.77 ±0.57	6.84 ±0.32	4.59 ±0.13	6.93 ±0.22	6.49 ±0.23	8.37 ±0.20	5.46 ±0.15	X	X
24 Mbps	**8.22 ±0.28**	4.21 ±0.08	6.88 ±0.33	5.53 ±0.18	4.57 ±0.13	5.99 ±0.12	5.75 ±0.10	7.55 ±0.29	6.17 ±0.15	X	X
36 Mbps	**11.03 ±0.44**	6.02 ±0.46	10.67 ±0.48	7.67 ±0.25	4.57 ±0.37	6.25 ±0.14	7.65 ±0.16	8.02 ±0.22	7.56 ±0.19	X	X
48 Mbps	**10.93 ±0.36**	5.34 ±0.12	7.55 ±0.55	7.40 ±0.24	5.66 ±025	9.65 ±0.27	7.51 ±0.17	7.33 ±0.19	8.17 ±0.20	X	X
54 Mbps	**10.93 ±0.32**	6.49 ±0.09	8.34 ±0.34	7.79 ±0.21	7.77 ±0.35	13.00 ±2.73	7.55 ±0.18	8.64 ±0.16	8.78 ±0.40	X	X

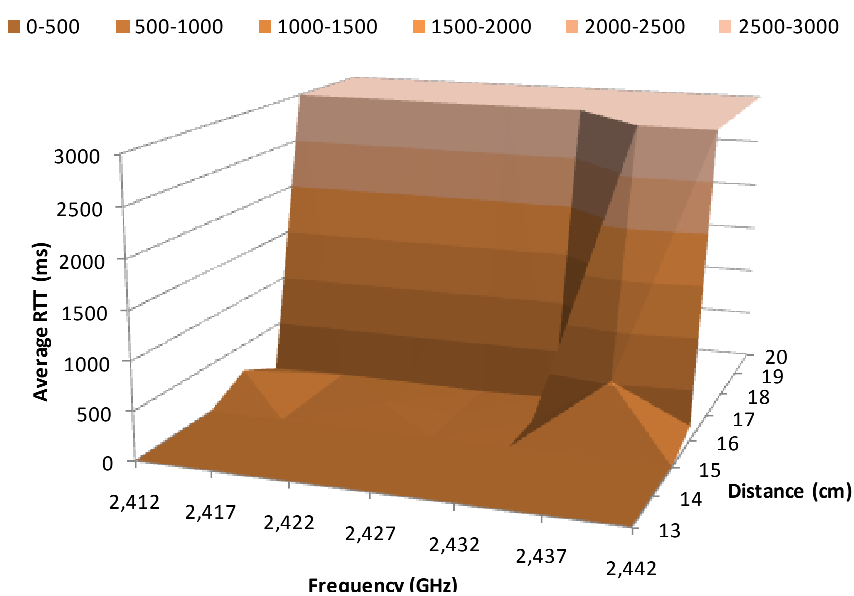

Figure 6.7. Average RTT and maximum distance for 1 Mbps at 26°C.

Table 6.15 shows the analysis of variance of 1Mbps measurements at 26 °C.

Table 6.15. ANOVA for 1 Mbps at 26°C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	106807534	7	15258219.1	58.0980224	1.4664E-19	2.2370703
Columns	1924465.18	6	320744.196	1.22128299	0.31472057	2.3239938
Error	11030413.4	42	262628.89			
Total	106807534	7	15258219.1	58.0980224	1.4664E-19	2.2370703

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant.

6.2.3.2 Performance of QPSK modulation and analytical study for 2 Mbps data transfer rate

Figure 6.8 shows the average RTT, in milliseconds, for 2 Mbps data transfer rate, when QPSK modulation is used, as a function of the working frequency work and the distance between wireless sensor nodes. The average RTT values for distances between 15 cm and 18 cm are kept below 500 ms for a frequency of 2,432 MHz, while at 2,437 MHz the average RTT increases up to 1,000 ms when there is a distance of 16 cm, and up to 3,000 ms when there is a distance of 17 cm. We observe RTT average values around 3 ms for distances below 15 cm, and for distances above 18 cm we obtained 3000 ms. At 17 and 18 cm, we receive very few packets. These present values of RTT near to 3,000 ms

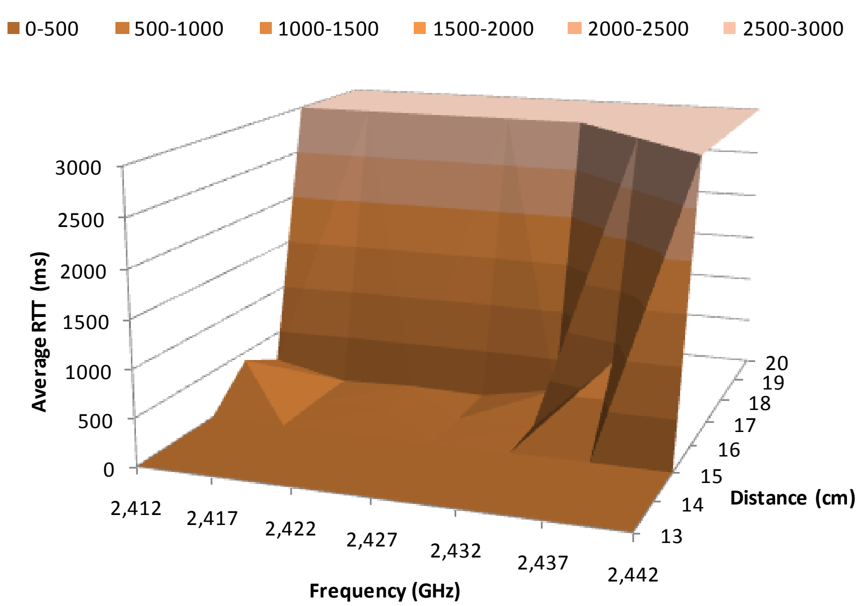

Figure 6.8. Average RTT and maximum distance for 2 Mbps at 26°C.

Table 6.16 shows the analysis of variance of 2Mbps measurements at 26 °C.

Table 6.16. ANOVA for 2 Mbps at 26°C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	100480369	7	14354338.4	40.1704344	1.3067E-16	2.2370703
Columns	4300487.5	6	716747.917	2.00580997	0.08629679	2.3239938
Error	15008107.9	42	357335.903			
Total	119788965	55				

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant.

6.2.3.3 Performance of CCK modulation and analytical study for 5.5 Mbps data transfer rate

Figure 6.9 shows the average RTT in milliseconds for 5.5 Mbps data transfer rate, when CCK modulation is used, as a function of the working frequency and the distance between devices. In this case, the RTT values for distances of 16 cm and 17 cm are kept below 500 ms for 2.432 GHz, while at 2.437 GHz the RTT value increases up to 2,000 ms for 16 cm, and near to 3,000 ms for 17cm. The biggest RTT variations are observed for distances between 15 and 18 cm, the measurements obtained beyond this range remain quite stable, between 3 ms and 4 ms for distances below 15 cm and close to 3,000 ms for distances above 18 cm.

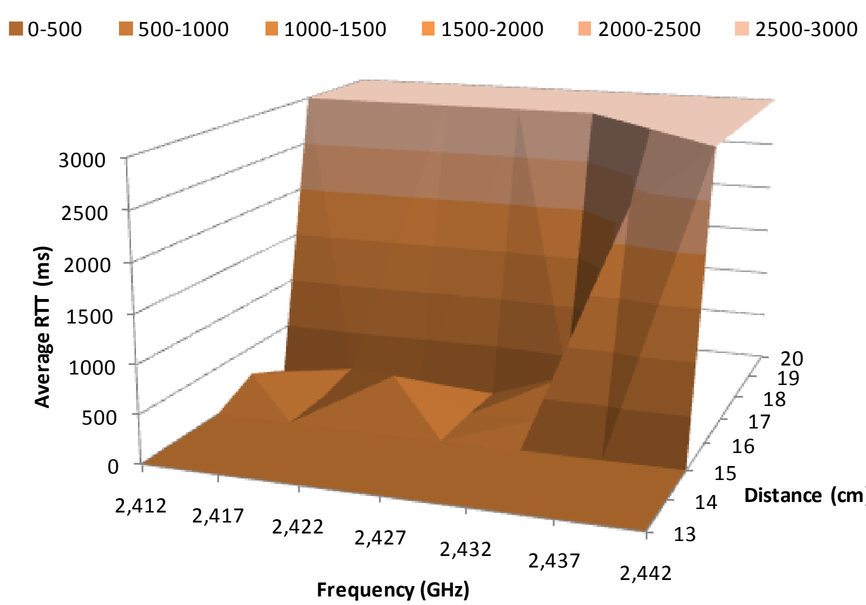

Figure 6.9. Average RTT and maximum distance for 5.5 Mbps at 26°C.

Table 6.17 shows the analysis of variance of 5.5Mbps measurements at 26 °C.

Table 6.17. ANOVA for 5.5 Mbps at 26°C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	112495732	7	16070818.8	48.1755146	8.2587E-20	2.20323159
Columns	5345097.71	7	763585.388	2.28900092	0.04231778	2.20323159
Error	16345858	49	333588.939			
Total	134186687	63				

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant.

6.2.3.4 Performance of CCK modulation and analytical study for 11 Mbps data transfer rate

Figure 6.10 shows the average RTT in milliseconds for 11 Mbps data transfer rate, using CCK modulation, as a function of the working frequency and the distance between devices. The average RTT values obtained for 16 cm remain stable (between 400 ms and 600 ms) at frequencies below 2,437 MHz, while at 2.442 GHz we did not measure the RTT of any packet. In 17cm, the average RTT values are very low for 2.412 GHz, 2.417 GHz and 2.427 GHz, but at other frequencies it reached 3000 ms. We obtained the same behavior than in the previous cases for distances below 15 cm and for distances above 18 cm.

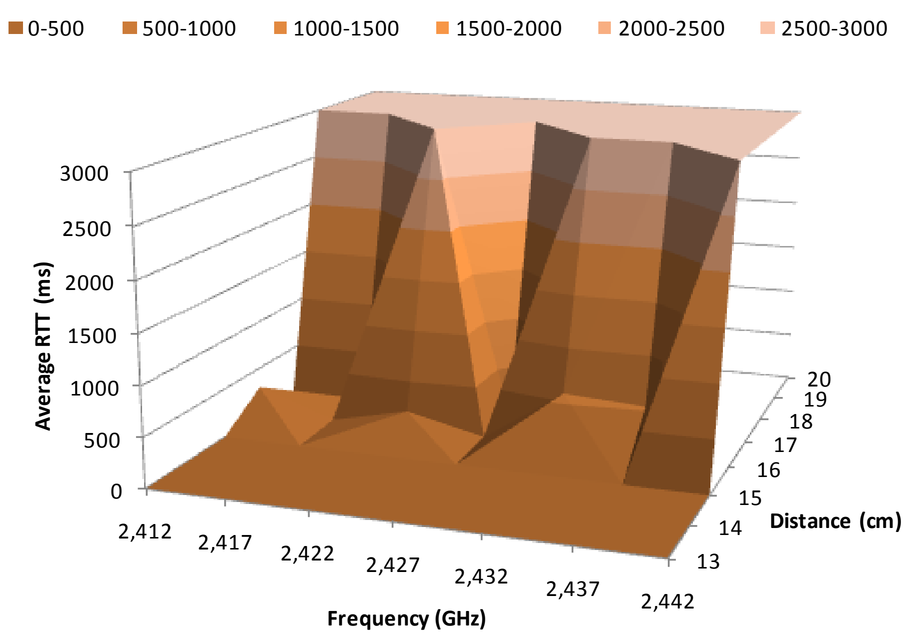

Figure 6.10. Average RTT and maximum distance for 11 Mbps at 26°C.

Table 6.18 shows the analysis of variance of 5.5Mbps measurements at 26 °C.

Table 6.18. ANOVA for 11 Mbps at 26°C

Origin of variations	Sum of squares	Degree of Freedom	Average Squares	F	Probability	Critical Value for F
Rows	113595680	7	16227954.2	44.3247445	4.7351E-19	2.20323159
Columns	3969516.86	7	567073.837	1.54889536	0.17331523	2.20323159
Error	17939635.4	49	366115.009			
Total	135504832	63				

For the same reasons explained in Section 6.2.2.1, we can conclude that the maximum distance depends significantly of the working frequency and the influence of data transfer rates is not significant.

6.3 Summary of Best Results and Comparison with Other Studies

Table 6.6 shows a summary of the best results for all tests. We can see that the best results are registered at 22 °C. At this temperature the maximum achieved distance was 26 cm using 2412 MHz for all data transfer rates. If we analyze the RTT values, we can see that the lowest value is registered for 2Mbps which uses QPSK modulation. Our measurements and tests have been carried out under controlled conditions and have been performed for four different temperatures. Our measurements let us to compare our results with the results obtained by other researchers.

On the one hand, the statement made by A.C. Balanis in [124] said that the absorption coefficient and the speed propagation were independent to the working frequency. Our results show that there is a clear dependency with the frequency. Moreover, at certain frequencies, the maximum distances are greater than others. We can also see that higher frequencies not always generate more signal deterioration and, consequently, shorter communication distances between devices. Throughout all graphics, we can see that using 2412 MHz at 22 °C, we obtain better RTT values and greater distances than the ones obtained for other data transfer rates. We can also observe that, the data transfer rates of 12Mbps at 20°C, reaches a distance of 26 cm, but the RTT value is 26.21ms. This value is six times greater than the RTT value offered by 2 Mbps at 22 °C.

On the other hand, the maximum obtained distance for our tests is 26 cm. If we compare our values with the ones provided by the estimations of X. Che et al., we can observe that our results are less optimistic than the approximations estimated in [133].

Moreover, our results show a relationship between the type of modulation and the network performance. There is better performance in some data transfer rates than in others. For example, 6 Mbps and 24 Mbps (in Table 6.19) show RTT values lower than the values of the rest data transfer rates (using the same modulation).

Table 6.19. Summary of best results

Data Transfer Rates	Best frequency (MHz)	Max. distance (cm)	Temperature (°C)	RTT (ms)	Modulation
1 Mbps	2,412	26	22	4.89	BPSK
2 Mbps	2,412	26	22	4.73	QPSK
5.5 Mbps	2,412	26	22	6.86	CCK
6 Mbps	2,412	26	22	8.00	OFDM
9 Mbps	2,412	26	22	9.31	OFDM
11 Mbps	2,412	26	22	14.72	CCK
12 Mbps	2,412	26	22	11.75	OFDM
18 Mbps	2,412	26	22	10.38	OFDM
22 Mbps	2,412	26	22	16.51	OFDM
24 Mbps	2,412	26	22	8.22	OFDM
36 Mbps	2,412	26	22	11.03	OFDM
48 Mbps	2,412	26	22	10.93	OFDM
54 Mbps	2,412	26	22	10.93	OFDM

It has been difficult to predict the obtained results because there are not previous references where authors analyze the behavior of EM waves at 2.4 GHz ISM band. Neither, we have not found any work where compare the performance of these modulations considering the environmental temperature. We have only found some works where authors provided some of parameters we have measured. Table 6.20 compares other works with the results obtained in this Thesis.

Table 6.20. Comparison of best results in several studies.

Reference	Technology	Working frequency	Length Wave	Modulation	Distance	Data transfer rates	Temperature
[116]	ElectroMagnetic waves	3 kHz	N/app	N/av	40 m	100 bps	N/av
[117]	ElectroMagnetic waves	100 kHz	N/app	BPSK	6 m	1 kbps	N/av
[118]	ElectroMagnetic waves	10 kHz	N/app	BPSK	16 m	1 kbps	N/av
[125]	ElectroMagnetic waves	1 kHz	N/app	BPSK	2 m	1 kbps	N/av
[126]	Optical Waves	N/av	420 nm	PPM	1.8 m	100 kbps	N/av
[127]	Optical Waves	800 kHz	N/app	BPSK	1 m	80 kbps	N/av
[128]	ElectroMagnetic waves	100 MHz	N/app	N/av	0.053 m	N/av	N/av
[349]	Acoustic Waves	12 kHz	N/app	MIMO-OFDM	N/av	24.36 kbps	N/av
[350]	Acoustic Waves	24 kHz	N/app	QPSK	2500 m	30 kbps	N/av
[351]	ElectroMagnetic waves	25 MHz	N/app	N/av	85 m	N/av	N/av
[352]	ElectroMagnetic waves	5 MHz	N/app	N/av	90 m	500 kbps	N/av
[353]	Optical Waves	N/av	N/app	N/av	11 m	9.69 Mbps	N/av
[354]	Optical Waves	N/av	470 nm	N/av	10 m	10 Mbps	N/av
[355]	Optical Waves	70kHz	N/app	ASK	70m	0.2 kbps	N/av
[356]	ElectroMagnetic waves	8-16 kHz	N/app	OFDM	N/av	11.60 kbps	N/av

Note: N/app: Not applicable, N/av: Not available

Reference	Technology	Working frequency	Length Wave	Modulation	Distance	Data transfer rates	Temperature
[357]	ElectroMagnetic waves	N/av	N/app	N/av	20m	16 kbps	N/av
Our measurements	ElectroMagnetic waves	2,427MHz	N/app	BPSK	0.17 m	1 Mbps	26
Our measurements	ElectroMagnetic waves	2,422MHz	N/app	QPSK	0.17 m	2 Mbps	26
Our measurements	ElectroMagnetic waves	2,427MHz	N/app	CCK	0.17 m	5.5 Mbps	26
Our measurements	ElectroMagnetic waves	2,427MHz	N/app	CCK	0.17 m	11 Mbps	26
Our measurements	ElectroMagnetic waves	2,412MHz	N/app	BPSK	0.26 m	1Mbps	22
Our measurements	ElectroMagnetic waves	2,412MHz	N/app	QPSK	0.26 m	2Mbps	22
Our measurements	ElectroMagnetic waves	2,412MHz	N/app	CCK	0.26 m	5.5 Mbps, 11 Mbps	22
Our measurements	ElectroMagnetic waves	2,412MHz	N/app	OFDM	0.26 m	6Mbps, 9Mbps, 12Mbps, 18Mbps, 22Mbps, 24Mbps, 36Mbps, 48Mbps, 54Mbps	22

Note: N/app: Not applicable, N/av: Not available

6.4 Mathematical Model

Finally, using data shown in Section 6.2, we can model the behavior of the signal as a function of the temperature, working frequency and modulation. The represented temperature range is from 16 to 27 ºC except to CCK modulation which only shows coherent values up to 22 ºC. For each modulation, we have represented all possible values which show coherent values.

The set of all our data can be represented as points of three coordinates *(f,t,d),* where *f* is frequency, *t* is temperature and *d* is the maximum distance between antennae. All points compose a surface S in the space which is the image of a continuous application:

$$\vec{r}: D \subset \Re^2 \rightarrow \Re^3$$

The set of points of the surface S can be represented as:

$$S = \{(f,t,d) \in \Re^3 : (f,t,d) = \vec{r}(u,v) = \langle f(u,v), t(u,v), d(u,v) \rangle \; con \; (u,v) \in D\}$$

Where *u,v* define the plane and $\vec{r}$ is a continuous vectorial function defined in *S*, i.e.:

$$\vec{r}: S \rightarrow \Re^3$$

When the pair *(u, v)* takes all possible values, the vector $\vec{r}$ draws a surface *S* in the space $\Re^3$. Given in mind these statements, we can define each point as the set of coordinates as follows:

$$(f,t,d) = f\vec{\imath} + t\vec{\jmath} + F(f,t)\vec{k}$$

Thus, we express the value of the maximum distance between antennas as a function of the operating frequency and the temperature of the medium.

$$d = F(f,t)$$

We have used Eureqa Formulize [358] to estimate the mathematical expression.

Firstly, we have used all obtained values to extract the mathematical model for underwater communications using BPSK modulation. Equation 6.1 relates the distance with the working frequency and the environmental temperature using BPSK modulation.

$$d = 669.9 * f + 360.8 * t + 0.393 * f * t^3 - 3341 - 8.921 * t^2 - 7.834 * f * t^2 - 0.004985 * f * t^4 \quad (6.1)$$

Where *d* is the distance in cm., *f* is the frequency in GHz and *t* the temperature in °C. This equation has a correlation coefficient of 0.8676 and an average absolute error of 1.036 cm

Using Equation 6.1, we can estimate the maximum distances for BPSK modulation as a function of the working frequency and temperature (Figure 6.11). As we can see, the maximum distance is obtained for 23.5 ºC working at 2.412 GHz. In addition, we can see that for temperatures of 27 ºC, the maximum reached distance is about 9cm, meanwhile for temperature around 16 ºC, the maximum distances is 21 cm for 2.412GHz and less than 19 cm. for 2.457 GHz..

Equation 6.2 relates the distance with the working frequency and the environmental temperature using QPSK modulation.

$$d = 594.9 * f * f + 335.9 * t + 0.3719 * f * t^3 - 3024 - 8.426 * t^2 - 7.336 * f * t^2 - 0.00475 * f * t^4 \quad (6.2)$$

Where *d* is the distance in cm., *f* is the frequency in GHz and t the temperature in °C. This equation has a correlation coefficient of 0.8831and an average absolute error of 0.961cm.

Figure 6.12 shows the estimation of maximum distances for QPSK modulation as a function of the working frequency and temperature. These approximations are obtained from Equation 6.2. The maximum distance (26 cm) is obtained for 23.5º C working at 2.412 GHz. Furthermore, we can see that for temperatures of 27 cm, the maximum reached distance is about 7cm. and for temperatures of 16 ºC, we can obtain distances between 18,8 cm to 21,5 cm.

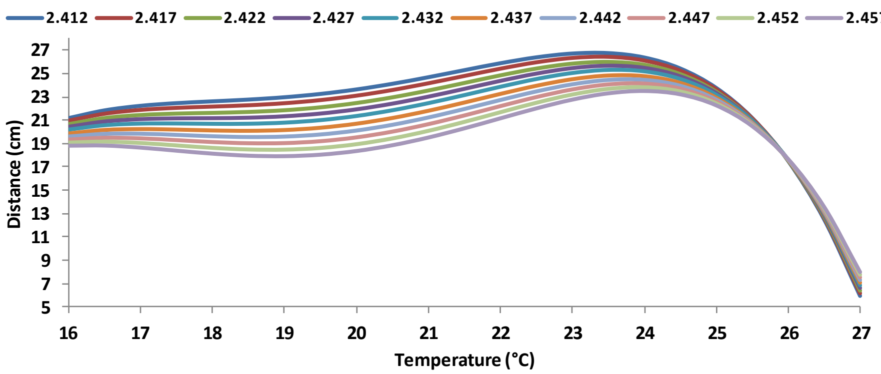

Figure 6.11. Estimated maximum distances for BPSK modulation.

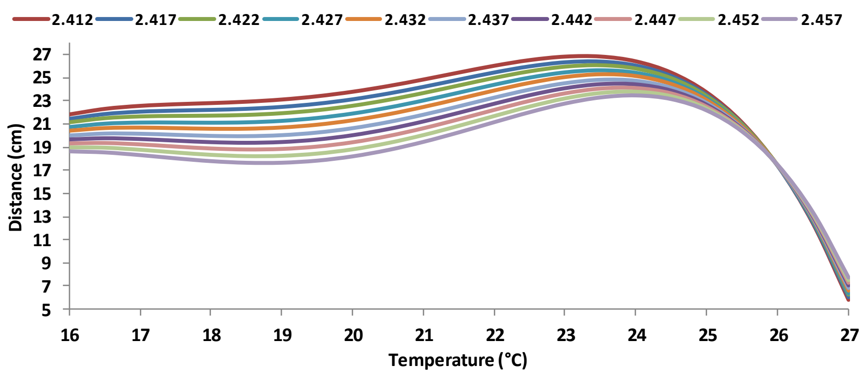

Figure 6.12. Estimated maximum distances for QPSK modulation.

Working with OFDM, we can estimate values between 16 to 22 °C. Equation 6.3 relates the distance with the working frequency and the environmental temperature using QPSK modulation.

$$d = 226.5 + 0.1493 * t^2 + 0.3006 * t * sin(0.04688 - t - 69.33 * f) + 0.1493 * sin(0.04688 - t - 69.33f)^2 + sin\big(tan(226.5 - t - 69.33 * f)\big) - 69.33 * f - 1.979 * f * \big(t - sin(0.04688 - t - 69.33 * f)\big) \quad (6.3)$$

Where d is the distance in cm., f is the frequency in GHz and t the temperature in °C. This equation has a correlation coefficient of 0.9238 and an average absolute error of 0.63 cm.

Figure 6.13 shows the estimation of maximum distances for OFDM modulation as a function of the working frequency and temperature. These approximations are obtained from Equation 6.3. The maximum distance (26cm) is obtained for 21º C working at 2,412 MHz. We can also see that for temperatures of 22 ºC, the maximum reached distance is about 25 cm. and for temperatures of 16 ºC, we can obtain distances between 15 cm to 21 cm.

Finally, CCK transmission scheme can be modeled by Equation 6.4 which relates the distance with the working frequency and the environmental temperature.

$$d = 1538 * f + 4.057 * f * t^2 + 0.003264 * t^4 - 2981 - 7.857 * t - 0.2975 * t^3 - 9.28 * f^3 * t \quad (6.4)$$

Where d is the distance in cm., f is the frequency in GHz and t the temperature in °C. This equation has a correlation coefficient of 0.8635 and an average absolute error of 1.16 cm.

Figure 6.14 shows the estimation of maximum distances for CCK transmission scheme as a function of the working frequency and temperature. These approximations are obtained from Equation 6.4. The maximum distance (26 cm) is obtained for 22.5º C working at 2,412 MHz. In addition, we can see that for temperatures of 27 ºC, the maximum reached distance is between 10 cm to 15cm. and for temperatures of 16 ºC, we can obtain distances between 17 cm to 22 cm.

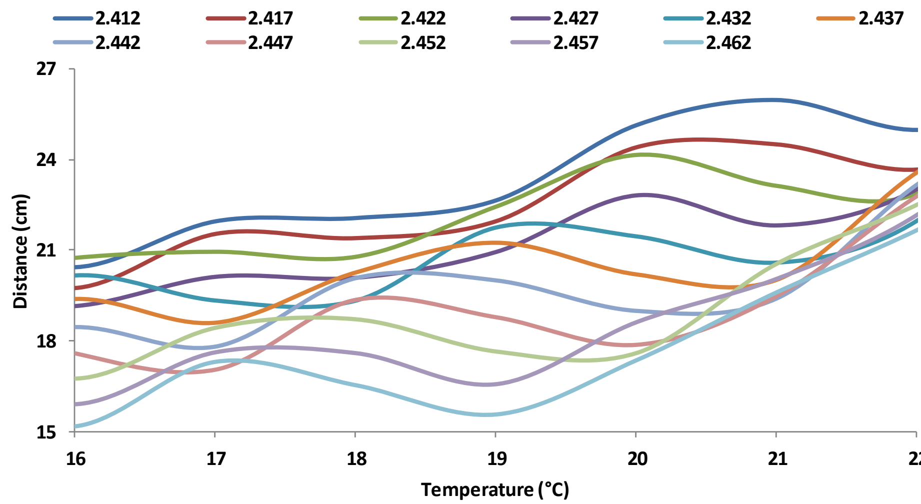

Figure 6.13. Estimated maximum distances for OFDM modulation.

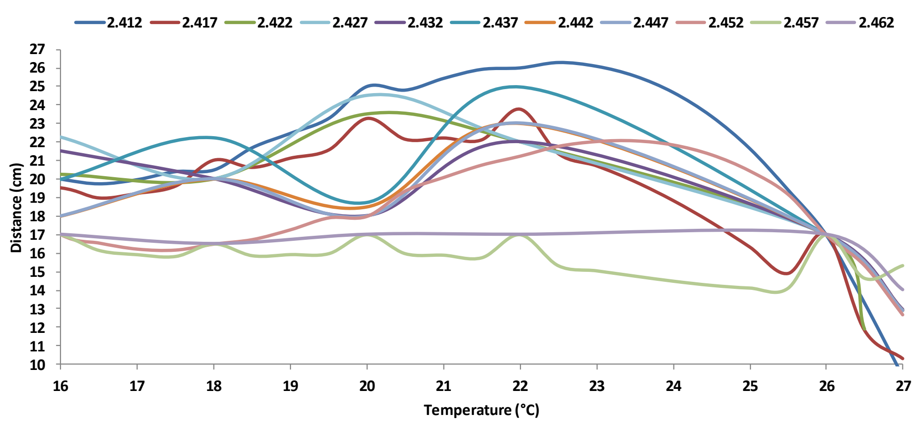

Figure 6.14. Estimated maximum distances for CCK transmission scheme.

6.5 Conclusion

Underwater Networks presents several application fields such as monitoring applications, as oceanographic data collection, pollution monitoring/detection, and off-shore oil/gas field monitoring. They can also be used for exploration applications such as submarine detection, loss treasure discovery, and hurricane disaster recovery [114] [178].

In this chapter we have analyzed the behavior of EM signals in underwater environments, for 16°C, 18°C, 20°C, 22°C and 26ºC and its dependence with the working frequency. Previous published works showed that the EM waves behavior has no relationship with the working frequency in freshwater. However, we have observed that there is an obvious relationship with the working frequency, type of modulation used and the environmental temperature. In addition, we have added a comparative of BPSK, QPSK, CCK and OFDM schemes for several temperatures. This type of analysis has not been performed in previous studies. We have compared our result with theoretical estimations and we have checked that these values were more optimistic than those obtained on the real environment. Moreover, we have seen that the temperature of the water affects the distance. For this reason, we have modeled the value of maximum distance between devices as a parametric function of the working frequency and the temperature of medium.

Although our proposal provides short communication distances in underwater wireless sensor networks, we can use it for precision monitoring such as ecosystems contaminated by invasive plants (especially in ponds where there are some poisonous plants that can contaminate the water) or hazardous waste (e.g. in swamps, the quality of the water is different depending on the season because the water may contain some organic material that may be affected when it is warmer because the pH is different). In both cases the water cannot be used for human consumption, but, in some cases, it can be used by industries to run their plants and supply the water cooling system. Moreover, our proposal can be used to control the pollution of the water, which may come from industries and nearby roads, accurately.

Another application is for communicating with some parts of the neutrino telescope [359]. The neutrino telescope is an underwater structure located at the bottom of the Mediterranean Sea. Researchers are seeking ways to connect a hydrophone, for the positioning system of different parts of this structure. Until now, they have been using cables and penetrators, to connect the different parts. These pieces have a high economic cost. Using wireless communications, we would be reducing the cost of this material and would avoid the critical connections that can propagate a fault (or leak) through the system. Finally, the fact, that the distances between the devices are extremely small (practically in contact), means that the depth of this infrastructure is not a problem for wireless transmission of information. There are other applications such as, military applications, marine monitoring and even industrial applications such as marine fish farms [178], to reduce the deposition of organic waste on the seabed and to fight against environmental contamination

The measurements shown provide several benefits. On one hand, the use of IEEE 802.11 standard is cheap (IEEE 802.11 devices are very cheap nowadays) and, on the other hand, it provides high data transfer rates, for the inclusion of all types of sensed data, even images.

Finally, work presented in this chapter has been published in the following references [174], [175], [176], [177] and [360].

Chapter 7

Application of WSN in Marine Environments

7.1 Introduction

Aquaculture is defined as an activity aimed at producing and fattening aquatic organisms such as fish, mussels, oysters or other shellfish and vegetables. It is also defined as the breeding under controlled conditions of species that are developed in the aquatic medium. The most developed cultivations are the edible species belonging to the molluscs, crustaceans and fish groups. These three groups and the production of algae constitute the fourth biggest group of aquaculture activity. Although, marine aquaculture originates a smaller environmental impact compared with other productive sectors and coastal activities, some impact is produced. These effects should be identified to eliminate and/or minimize them.

When marine fish farm viability is studied, marine biologists should make an orographic and hydrodynamic environmental evaluation of the farm cages mounting area [361]. Many water parameters should be measured: pH, Salinity, Temperature, dissolved Oxygen (dO_2) the transparency, the suspended solids (SS), Ammonium, Nitrates, the Total Nitrogen (NT) or match soluble reagent (PSR), among other [362] [363]. Other parameters such as Total Organic Carbon (TOC), soluble phosphorus, soluble total nitrogen, redox potential or grain-size composition give us information of the physic-chemical characteristics of the sediments. This information is used to select the most appropriate place for the cages and the most appropriate environmental measuring system. In open sea facilities, nutritious concentrations in silts tend to increase and they are usually located at the address of the predominant current, outside the polygon of cultivation [361].

One of the main issues in aquaculture is the high cost of the lost food when the fish are fed. Furthermore, this wasted food is deposited in the seabed and generates an environmental impact on the surrounding area. It causes failure to uphold aquaculture legislation.

When the fish are fed in marine fish cages, it is difficult to control the point of cessation. The lost food in the cages is close to 8.26%, of the total food. Bearing in mind that food expenses represent almost 60% of the total costs of marine farm exploitation, the food that gets lost in the feeding process of these facilities should be controlled [364]. This undesired waste is dispersed in the pelagic system and deposited on the seabed [365]. It causes some impact on the benthic habitats, and can affect to sensitive communities such as seagrass meadows or rocky reefs, and it also reduces the economic benefits of the fish farm because the wastage of the uneaten food.

As Figure 7.1 shows, the most important producer of fish from aquaculture is Asia with approximately twenty times more than America or Europe. If we analyze the European total production of fish from aquaculture, we can see that Spain is one of the primary European aquaculture producers in terms of volume (See Figure 7.2) [366]. Moreover, in recent years, Latin America, and especially Chile, has emerged as an aquaculture power [367]. This has meant that many of the studies and researches are written in the Spanish language.

The aquaculture is the fastest growing food sector. The production has doubled since 1987 and in 2040 the global demand for fish will again be doubled. In 2001, nearly of 30% of seafood consumed came from farms, although it is estimated that this value will be multiplied by 7 in the next 25 years to keep global fish consumption. For this reason, aquaculture should be understood as a way to offset the collapse of fish wild populations.

Seeing these values and the estimation of production, we think it is necessary to improve the current methods in order to reduce the environmental impact of the farms in the surrounding areas and the economic losses due to food waste.

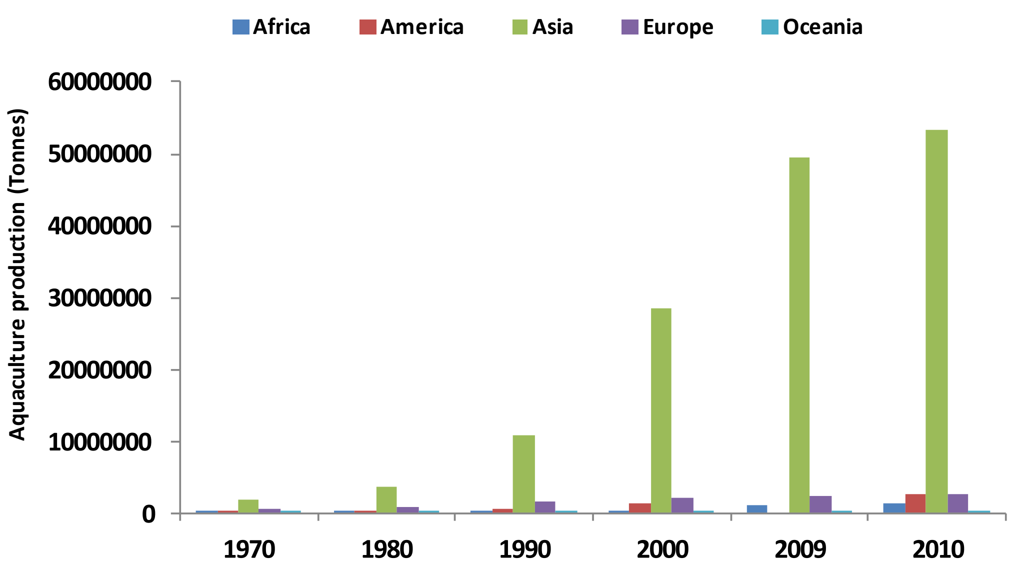

Figure 7.1. Total production of fish from aquaculture in the world.

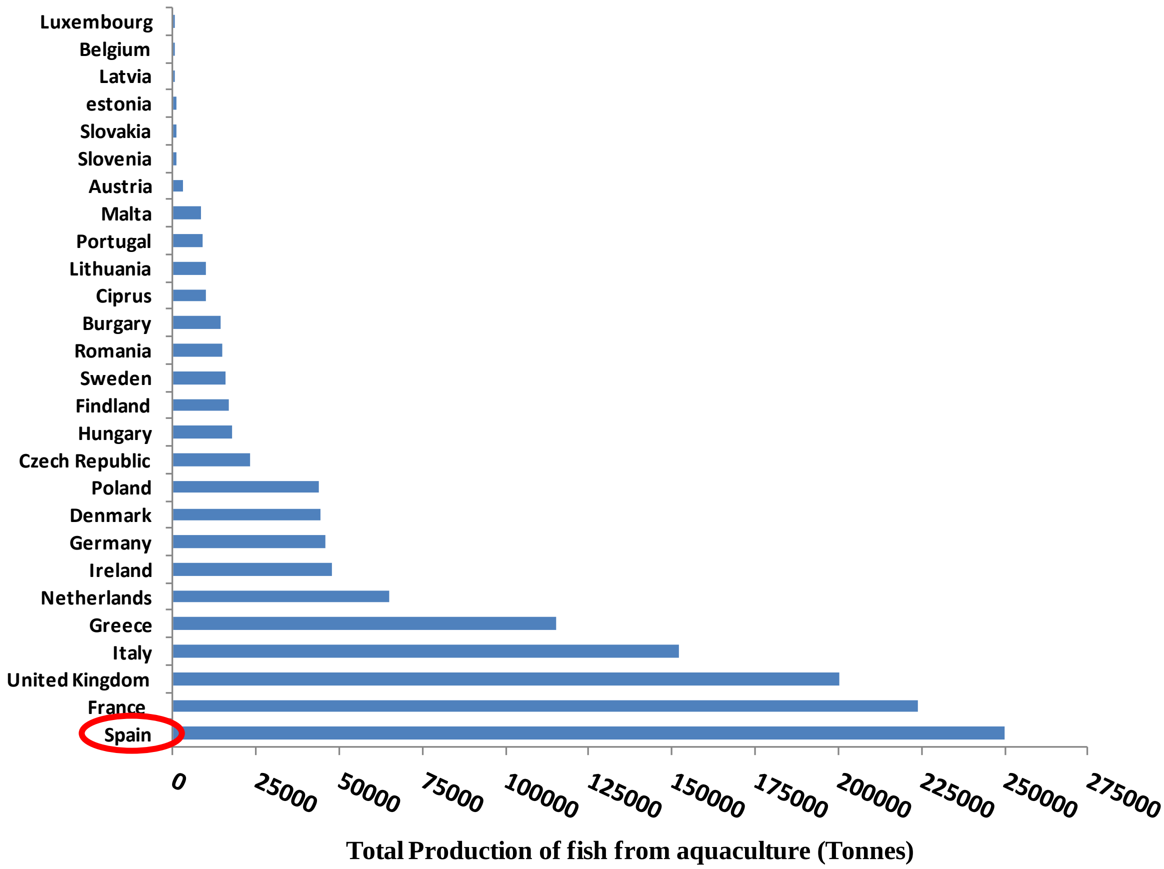

Figure 7.2. European total production of fish from aquaculture in 2010.

In this chapter, we are going to show the proposal of a wireless sensor to deposition monitoring. In addition, we are going to present a low cost turbidity sensor which helps us to control de quality of water. To understand the deployment of these sensors, firstly we will see the main problems that fish farms managers have. We will also see the seabed depositions estimation. After presenting our proposal, we will show the estimation of the number of sensor nodes we need. Finally, we will see a simulation of the amount of food we should use in regular procedure and with our proposal. Last Section shows the conclusion of this chapter.

7.2. Problem Description

One of the main problems to be considered in several marine related activities, such as the marine fish farms and their surroundings, is the amount of uneaten feed and the faecal waste generated by the fish and deposited on the seabed under the cages. The wastage accumulation in the seabed causes notorious changes in the silt chemistry of the nearby farm areas. It impacts the fauna and flora, and the whole sustainability of the system.

Nowadays, the feeding process is carried out distributing the food by hand or impelled canyons by air. It can also be used crafts with fixed pipes in each cage impelled by air compressors can be used or by self-demand troughs. The control of the exact moment when the food begins to fall to the seabed is currently done by a camera which is introduced and removed from the water every time the fish should eat. Scuba-divers are also in charge of this task. Sometimes the conditions of the water are not always good and suitable for immersions, but fishes must be fed all year round.

The maintenance of equipment and the own feeding process have associated high economic costs.

The currently mathematical formulations can estimate the amount of food in the tank by knowing the number of fish in the cage and supposing that all the fish in the cage have the same weight and size. But in most cases, there are some groups of fishes which present different behaviour. Some ones usually acquire dominant aptitude and tend to eat more. However, others may acquire a submissive attitude and eat less or even after the dominant fish have eaten. So, we will probably have groups infra and overfed.

Additionally, we have observed that fishes usually adopt particular behaviours in function of the environmental conditions. It may happen that the fishes do not eat the quantities envisaged due small changes in water temperature, so we will be wasting food. According to some studies, fishes have certain behaviour patterns that can help us to know the level of satiation of them. When the shoal is hungry, they increase their physical activity and swim faster and near to the surface and due to be on cage, fishes usually swim following the perimeter of the cage. Therefore, our system should consider this increase in speed and depending on these results, we will obtain several results. With the set of sensors, the system will be able to discriminate between whether the fish are hungry or if they are just frightened by a predator which prowls around [178].

Therefore, a significant advance in aquaculture, from the standpoint of feeding control, would be the real-time monitoring of the activity of the fish and the detection of the fall of uneaten feed.

For this, we want to develop some sensors to measure these parameters. The set of these sensors can help us to interact with the feed dispensing system. This system will control the amount of food per unit of time to drop into the water.

Some of these sensors, we can buy it directly (although it has a very high cost), but others do not exist and we would need to develop them. Some of the most important sensors to install in a fish cage are the following ones:

- Sensors that sense the cage water column temperature, dissolved oxygen, and turbidly: The species usually eat more when temperature is higher and grow best between some specific temperature ranges. In addition, fishes do not feed well at low oxygen concentration. These parameters and the water turbidity are limiting factors in fish growth.
- Sensors that senses in specific places the water current and salinity: It is important to define the water current in order to calibrate the measures of speed sensors and to define the uneaten food spread. A very abrupt salinity change may mean the death of many fish. Salinity changes should not be too high.
- Sensors that measure the fish speed: In most species, the speed of the fish is directly related to their hunger. If the fishes are moving quickly, it is because they are hungry (but it could also be caused by the appearance of a depredator near the cage).
- Sensors that let us know when the feed begins to fall on the seabed and its quantity: One of the main issues to take into account in sustainability in marine fish farms is how faecal

pellets and uneaten feeds are spread under the cages. These depositions are settled some distance from the farm implying an adversely impact in the coastal environment.

- Sensors to detect and follow the water pollution of the water column in the cage surroundings: The quality of water is one of the most important parameter related to the fish growth. If water would contain heavy metals, these fish would be unfit for human consumption. The dumping of other substances may cause massive death of fishes inside the cage.

Figure 7.3 shows a fish cage with the most important sensors to improve the sustainability of a marine fish farm.

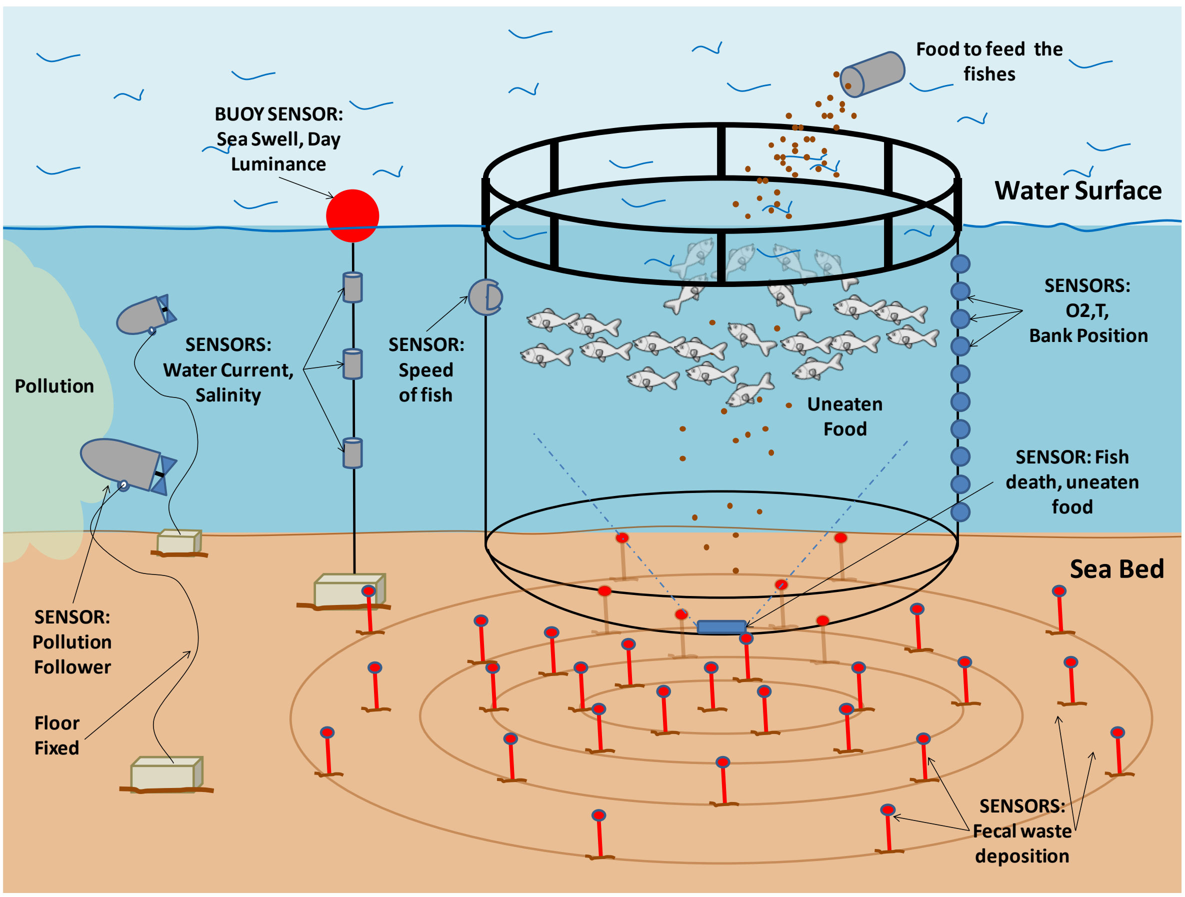

Figure 7.3. Marine fish cage with a sensor network for monitoring the fishes activity

Considering all of these considerations, it is evident that a monitoring and control sensor system for fish feeding in marine fish farms is justified. An adequate feeding distribution system will be essential to assure a homogeneous growth of the fish cultivation [368]. Moreover, the system will be able to detect and warn special cases such as temperatures out of the regular values for a specific season, which will allow us to see the effects of the climate change.

7.3. Seabed Depositions Estimation

As we have read at the beginning of this chapter, one of the most important problems in aquaculture activity is how to control the amount of uneaten feeds which is spread under de cages and surrounding areas. Due to the underwater currents this food can be settled some distance from the farm implying an adversely impact in the coastal environment. This Section shows the analytical estimation of deposition in seabed in terms of studied dispersions models, current speeds and settling speed as a function of the particle features.

We can find several studies about the factors influencing the sedimentation and accumulation of organic material under and near the fish cages [369][370][371]. We are interested on their distribution area for determining the best sensor distribution along the seabed surface. To do the estimations of waste deposition, we should take into account the following parameters:

- Biomass of the fish
- Metabolic rates of the fish
- Settling rates of excess fish feed
- Settling rates of fecal pellets
- Feeding rates
- Amount of excess (waste) feed
- Consumption of waste feed by other species
- Rate of decay of organic particles on the bottom
- Sinking velocity of the particles
- Velocity and direction of the current
- Depth-varying currents
- Water depth

It is also important to estimate the concentration or the amount of different elements like carbon, nitrates and phosphates generated from wasted food and feces. The physic-chemical characterization of the water can be used to estimate the pollution level in an area. Stigebrandt et al. present a dispersion model [372][373] which gives us the average value of carbon emission from the cages. Equation (7.1) represents the mean carbon emission from cages in g/(m^2•Day).

$$F = \frac{1}{2} \cdot \frac{T_P}{\Delta f} (FCR - FCR_t + 0.1) \tag{7.1}$$

Where, FCRt is the theoretical feed conversion ratio; FCR is defined as the factual feed conversion ratio; TP is the Total Proteins and Δf is the total area of the cage.

According to [372], it is possible to consider that FCR − FCRt=0.3. This means that the waste feed is equals to 0.3 kg per each kg of produced fish. For out calculation, we have assumed that Tp can be a value between 20 and 30 (depending of the fish species) [374], and that the size of cage is between 6 and 25 m of diameter. Figure 7.4 shows the estimated carbon emission in function of the cage size and de value of TP

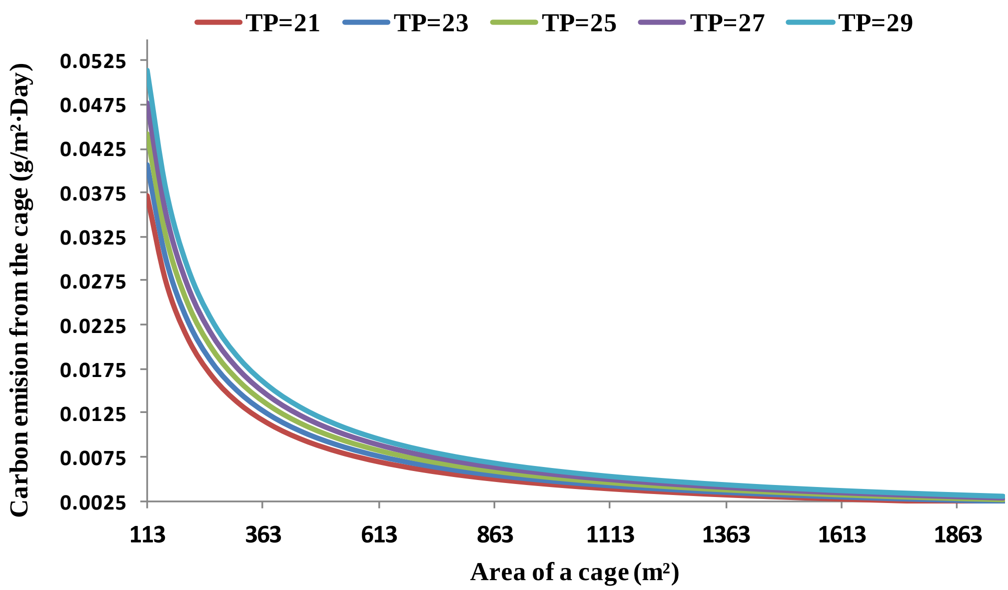

Figure 7.4. Carbon emision from the cage

Considering the measurements gathered in reference [372], it is possible to estimate analytically the sedimentation coefficient S (expressed in Svedbergs) as a function of the distance, for a sinking speed per sinking time equal to 15 (δT=15). This estimation is shown in Equation 7.2 (it has a correlation coefficient of 0.9974).

$$S = -1 \cdot 10^{-7} r^4 + 1 \cdot 10^{-5} r^3 - 0.0004 r^2 + 0{,}0012 r + 0{,}077 \tag{7.2}$$

Where S represents de sediments in svedbergs and r de distance from de center of cage.

Figure 7.5 shows the depositions of a marine fish farm with 6 cages, each one with 15 meters of radius, that are placed in the positions (20, 20), (60, 20), (100, 20), (60, 30), (60, 70) and (60, 110) for δT=15.

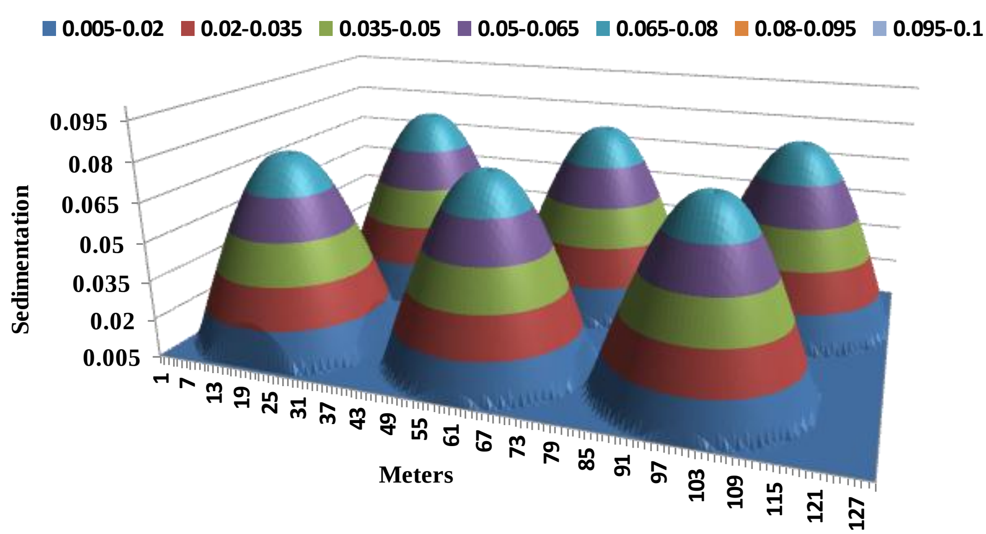

Figure 7.5. Sedimentation for δT=15, in a fish farm with 6 cages.

7.4. Wireless Sensor Node for Depositions Monitoring

In this section we present the proposal of a sensor node for deposition monitoring. We explain its operation and its mobility. Finally, we will do an estimation of the amount of sensors we will need to cover an area

7.4.1. Sensor Nodes Operation

Ultrasonic sensor works using the "pulse-echo" principle combined with triangulation techniques. Sound waves can be irradiated only when there is a medium. This medium can be, in the case of ultrasound, a gas, a fluid or a rigid material. Ultrasonic sensors are normally used with atmospheric pressure. When the control unit sends a digital pulse, the electronic circuit excites the aluminum membrane with rectangular pulses in the resonant frequency to generate vibrations typical of 300 μs (although this value depends on the application and the kind of transducer). Then, it emits ultrasonic waves which are reflected with the obstacle. They, in turn, vibrate a stabilized membrane. The piezoceramics convert the vibrations into an analog electrical signal, which is amplified by the sensor and converted into a digital signal. Figure 7.6 shows the operation diagram of a common ultrasonic sensor.

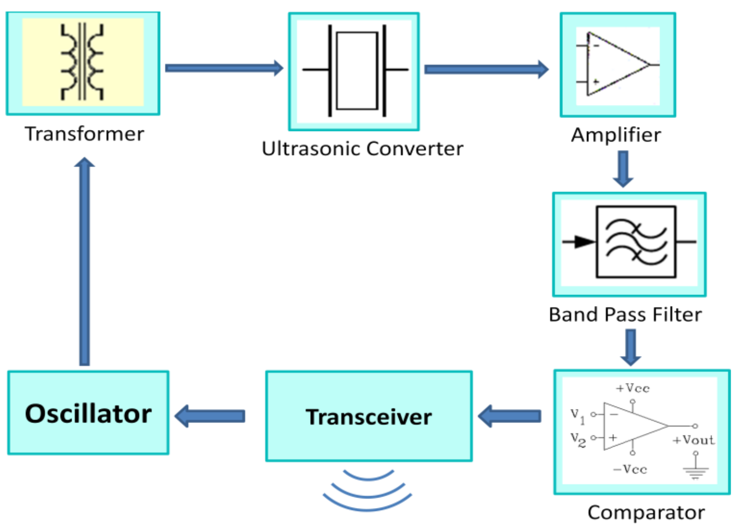

Figure 7.6. Operation diagram of an ultrasonic sensor

Communication between sensor nodes can be performed using acoustic hardware built-in to sensor modules [375].

In order to cover a large area (as wide as possible), the sensor detection angle should be big in the horizontal plane. On the contrary, it should have a small angle in the vertical plane in order to avoid disturbing reflections from other obstacles. Figure 7.7 shows the radiation patterns in the vertical plane (blue) and in horizontal plane (orange) for the UM18-X111X sensor series (manufactured by Sickusa [376]). The sensor is placed in (0,0). These sensor models are able to locate objects at distances between 30 mm to 250 mm, with a resolution of 0.36 mm. If this sensor is fixed in a place, without movement, it is able to cover a measuring area of about 120 mm.

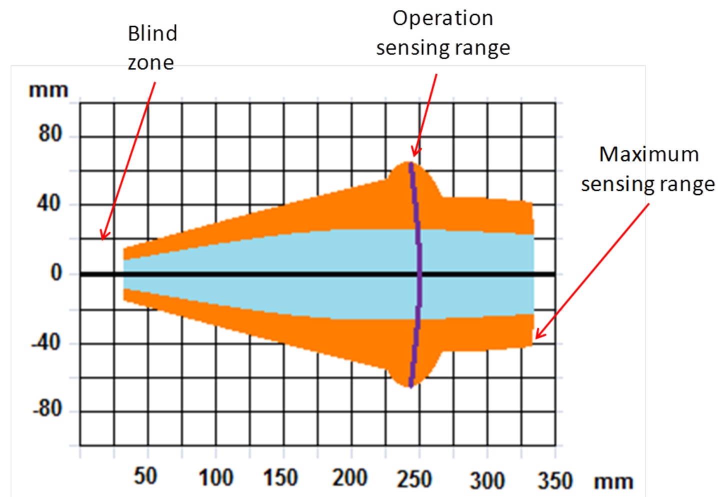

Figure 7.7. Radiation diagram for UM18-X111X sensor series

7.4.2 Sensor Mobility Model.

Some studies have demonstrated that controlled mobility can be exploited practically [377]. So, in this section we are going to study how we can take advantage of the sensor mobility. Because our sensors are held to an inverted pendulum system, which offers greater mobility, the measured area of each device is much higher. Each one of the sensors is anchored to the ground with a brace of 20 cm. Therefore, each sensor would be able to cover an area of approximately 1.32 m^2, forming a circle with a diameter of 52 cm, as it is shown in Figure 7.8. In order to set the maximum sensing area, we defined the maximum slope that it may suffer due to ocean currents. It is approximately 40 degrees, although this value may be different depending on the location of the marine fish farm.

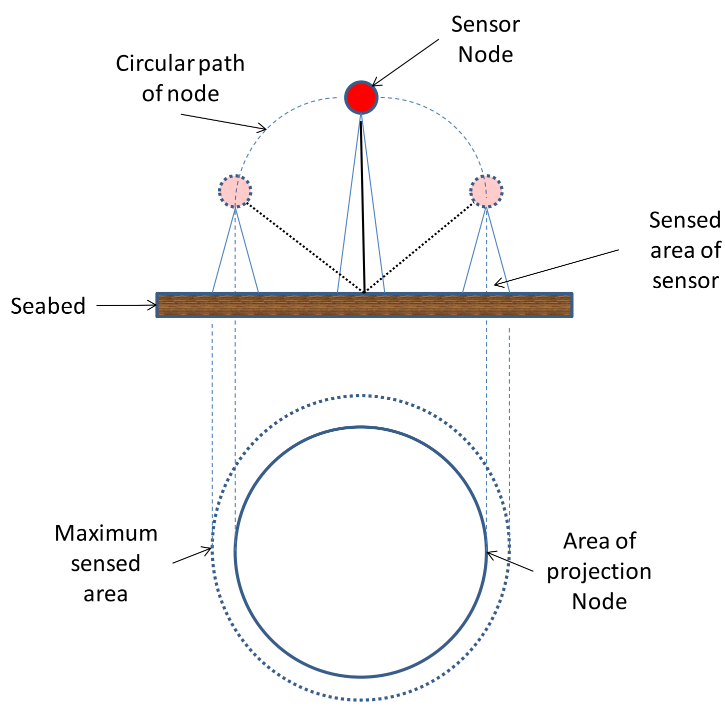

Figure 7.8. Maximun sensed area by one sensor

In order to model the movement of our sensor node, we use basic principles of body dynamics. The system performs a series of movements that can be decomposed into two parts. In this section we discuss the motion in the XZ plane, mainly due to the action of the water flow, considering only its magnitude and the motion in the XY plane, where the node describes a circle of radius R (the the position of the node on the XY plane is also related to the direction of water flow). Thus, we have to estimate the equation of the position of the node in a three-dimensional space. Figure 7.9 shows the explained situation. We have used a Cartesian axis system.

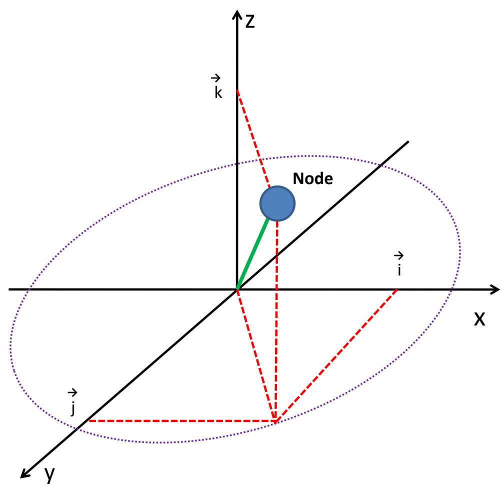

Figure 7.9. Wireless Sensor node movement

From the point of view of the vertical plane motion, we used Archimedes' Principle, but taking into account that the sensor node floats (it is inside a ball with air), but it is fixed to a point on the seabed. Our system has the mass *m* of the sensor, secured by a straight wire of length *l* to the seabed. The wire has a tenseness *T* on the mass that prevents the sensor to float. Figure 7.10 shows this situation. In order to define the equation of the sensor movement in the vertical plane, the second Newton's law is used, which states that the system remains in balance, if the water upward force is equal to the total weight of the node and the tenseness of the wire. Some easy estimations let as find the angle of the wire of the sensor ball (θ) respect to the vertical line position. It is shown in Equation 7.4.

$$\theta = \sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial T}\right) \qquad (7.4)$$

Thus, for the $P_{X,Z}$ plane analysis, we can draw our node position on the P_Z axis following equation 7.5.

$$P_Z = l \cdot cos\left(\sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial T}\right)\right)\vec{k} \qquad (7.5)$$

Where ρ_s is the density of the sensor node (the ball), ρ_f is the fluid density, V_{node} is the sensor node volume, g is the acceleration due to earth gravity, m is the sensor node mass, and finally v_{water} represents the seawater flow.

From the point of view of the horizontal plane motion, the sensor node draws a circle of radius R because of the water flow direction and the wire. Where $= l \cdot \sin(\theta)$, the wire has length l and the angle θ is estimated by Equation 7.4. Figure 7.11 and 7.12 show the status of the sensor node and the parameters involved in its movement. Thus, for the $P_{X,Y}$ plane axis, assuming a flow direction with angle α, we obtain Equation 7.6 (all parameters have been previously defined for equation 7.4).

$$P_{X,Y}= l \cdot \sin\left(\sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial T}\right)\right) \cdot \cos(\alpha)\,\vec{\imath} + \; l \cdot \sin\left(\sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial Tt}\right)\right) \cdot \sin(\alpha)\,\vec{\jmath} \quad (6)$$

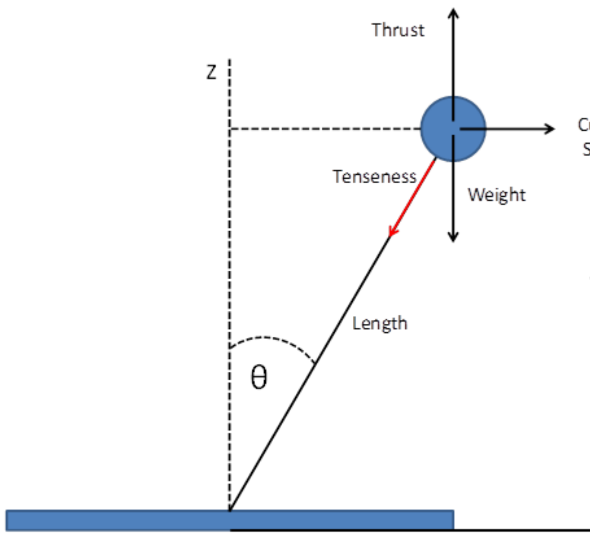

Figure 7.11. Movement in the vertical plane

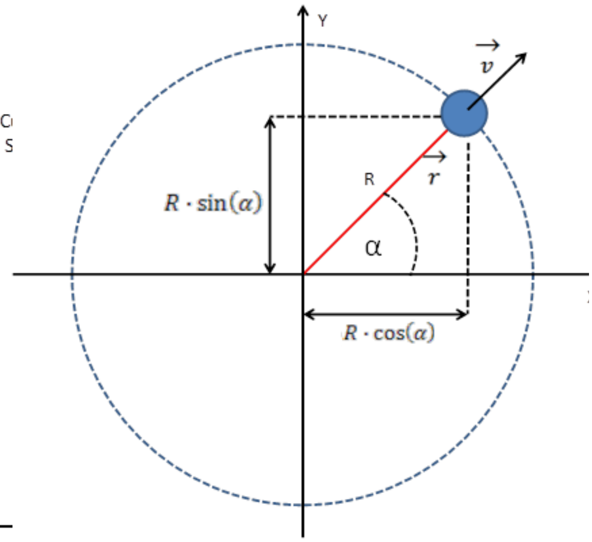

Figure 7.12. Movement in the Horizontal plane

The three-dimensional movement of the sensor node is given by the sum of the vertical plane and the horizontal plane. Expression 7.7 shows the sensor node movement in the three axes.

$$P_{X,Y,Z}= l \cdot \sin\left(\sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial T}\right)\right) \cdot \cos(\alpha)\,\vec{\imath} + l \cdot \sin\left(\sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial T}\right)\right) \cdot \sin(\alpha)\,\vec{\jmath} + \; l \cdot cos\left(\sin^{-1}\left(\frac{m}{V_{node} \cdot g \cdot (\rho_f - \rho_s)} \cdot \frac{\partial v_{water}}{\partial T}\right)\right)\vec{k} \quad (7.7)$$

Where, all parameters have been previously defined.

7.4.3 Sensor Nodes Distribution

We have seen in Figure 7.5 that there are more sediment concentrated in the center of each cage and this value decreases when the distance from the center of the cage increases. When the variations of faeces and pellets deposition and sedimentation are lower, we can decrease the number of sensors. Sensors that are closest to the center of the cage have to send more number of messages about the sedimentation information due to the constant change of the depositions than the ones located in the outer zones of the cages. Bearing in mind all this information, we have estimated the density of sensors needed as a function of the distance to the center of each cage. Figure 7.13 shows the sensor density for δT=15.

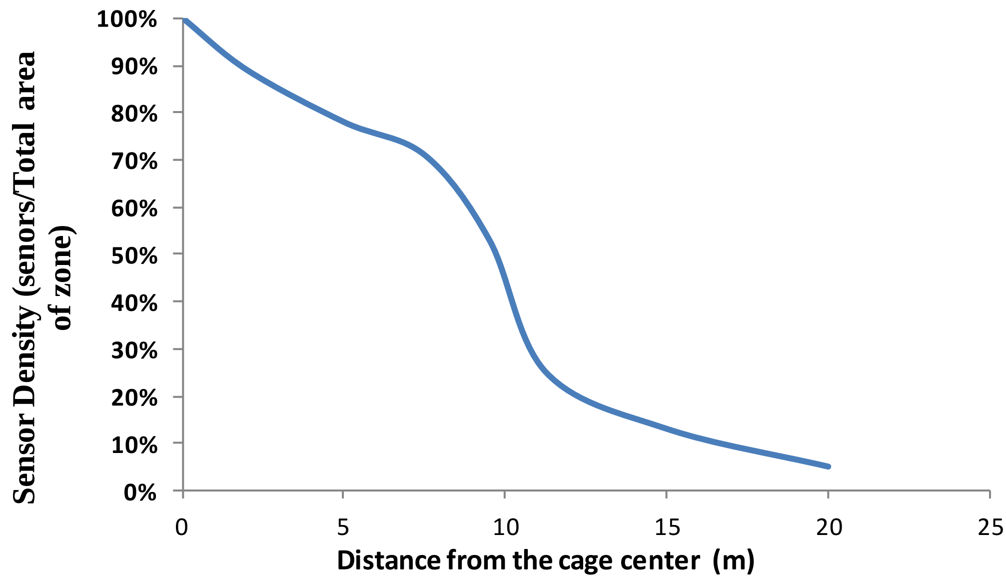

Figure 7.13. Sensor density as a function of distance to the center of the cage

Table 7.1 shows the number of sensors and the sensors density for δT=15. These estimations are based on the area to be covered for each zone specified in Figure7.5. The sensor density estimation for each zone is proportional to the deposition level in each zone. We have estimated it bearing in mind that the maximum number is registered in the center of the cage. The sensors are distributed uniformly in each zone. As we can see, the distribution of sensors up to 10 m. is fairly uniform. From 10 m. in advance, the number of sensors decreases considerably because the amount of depositions observed in this area is quite smaller, and therefore the variation of this parameter is also lower.

Table 7.1. Density of sensors in each area

δT=15			
Distance from the cage center (m)	**Resultant area (m^2)**	**Number of sensors**	**Sensors density**
1	3.14	3	100%
2	12.56	8	89%
5	78.5	46	78%
7.5	176.625	95	71%
9.5	283.385	114	53%
11.25	397.40625	75	25%
15	706.5	70	13%
20	1256	48	5%

7.5. Low Cost Turbidity Sensor

Nowadays, it is important to have wide knowledge in underwater parameters because large changes can be important in some areas such as aquaculture, pollution monitoring, sewage treatment or oceanography.

The Water Framework Directive [378] proposes to measure some physicochemical parameters like temperature, dissolved oxygen or salinity, among others, to evaluate the quality of all water bodies (including marine water till one nautical mile from the coast).

In lasts years, the most common methods to analyze the water and to define these variables were sampling in-situ and the subsequent analysis at laboratories. The use of sensors to perform this kind of measurements is becoming increasingly common because these methods can reduce the analysis cost of the physicochemical parameters. The use of sensor nodes can be a way to eliminate the manual process of sampling because the measurements are performed automatically in the environment (river, lake, fish farm…) by the sensor nodes. The use of sensors reduces costs avoiding going to the field for taking samples. When measurements and analysis are performed directly in the medium by using sensors, the sampling process is enhanced and we are sure that the number of samples is representative.

The lifetime of a physical sensor is longer than a chemical sensor. The chemical methods used at laboratories use reagents consumed during the analyses. Physical sensors also let us measure in real time. If we use several sensors forming a network along a river, it is possible to have measures along any type of environment such as a river bed or in the surrounding area of a marine fish farm. For these reasons, the use of sensor networks is growing day by day and now, it is easy to find many examples [161].

The turbidity is defined as the decrease of transparency of a water solution caused by the presence of dissolved or suspended particles. These particles reflected, scatter and attenuate the light [379].

Turbidity measurements are important for environmental monitoring and management. In some cases, the sampling process is complicated and it may alter the environmental conditions. The alteration of a sample can make it not being a representative sample, so it should not be taken into account. Turbidity is expressed in nephelometric turbidity units (NTU).

Turbidity values can vary by changes in the composition of the solids and some dissolved substances in water. In the seas, oceans and rivers those substances can have different origins and different effects. On one hand, the solids can come from the erosion of the emerged zones which provide nutrients to the water. On the other hand, the solids can come from different industrial effluents and in this case they can be dangerous for the environment. The suspended solids can also have a biological origin. They can be different type of microorganisms like phytoplankton, zooplankton or organic particles matter. Consequently, turbidity can indicate a wide range of situations (pollution, eutrophication or the increase of solids in the water mass).

The sediments in suspension can cause several environmental damages such as benthic smothering, irritation of fish gills and the transport of absorbed contaminants. These sediments also produce an attenuation of the light penetration and this affects to the photosynthesis process [380]. The light dispersion can be used to measure the turbidity at specific wavelength and at specific angle, usually 90º [379].

In this Section, we propose the design of a low cost turbidity sensor. In addition we have performed a set of measurements in sea water for several turbidity levels. Finally, we have performed a verification process to ensure that our system is working correctly.

7.5.1 Our Proposal

Our system is based on the use of an infrared LED as a source of emission and a photodiode as a receiver. Both elements are disposed at an angle of 180° and they are faced so that the photodiode can capture maximum infrared light from the LED. The infrared LED and the photodiode are placed at a distance of 4 cm.

TSUS5400 is an infrared emitting diode using GaAs technology molded in a blue-gray tinted plastic package. This infrared diode has a peak wavelength of 950 nm and its angle of half intensity is 22°.

S186P is a high speed and high sensitive photodiode in a plastic package. It is an IR filter, spectrally matched to GaAs or GaAs on GaAlAs IR emitters (≥ 900 nm). The large active area combined with a flat case gives a high sensitivity at a wide viewing angle. The angle of half sensitivity is ±65º. S186P is covered by a plastic case with IR filter (950 mm) and it is suitable for near infrared radiation.

The transmitter circuit is powered by a voltage of 5V while the photodiode is supplied with a voltage of 15V. To achieve these values, we use two voltage regulators of LM78XX series, where XX is 05, for the transmitter circuit, and 15 for the receiver circuit. This type of regulatory permits a maximum output current of 1 A.

In our system, the water turbidity is proportional to the potential difference registered in the resistance R3. To process the voltage values recorded in the receiver circuit a microcontroller is used. This element is responsible for taking the data and performs the necessary calculations to estimate the turbidity value of the analyzed solution. The model we have used is the PIC18F2525 which is fed at 5V. We can use the microcontroller to display information via a LCD display or to send the information through the RS232 port to a personal computer. Figure 7.13 shows the schematic of our turbidity sensor.

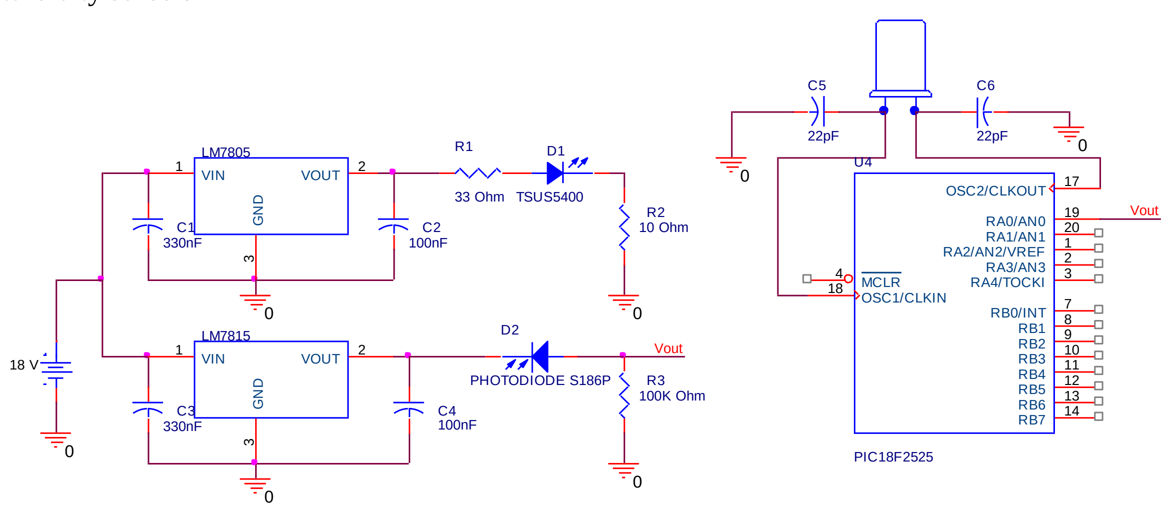

Figure 7.13. Esquematic of our low cost turbidity sensor.

7.5.2 Cost of Our Turbidity Sensor

The electronic components used in our turbidity sensor can be easily found. We have asked for their prize in a Spanish electronic distributor. The prizes of the main components are shown in Table 7.2. As Table 7.2 shows, the prize of the needed electronic components is very low.

Table 7.2. Price of main components

Component	Prize of components(in €)
Voltage regulator LM7805	0.80
Voltage regulator LM7815	0.86
IR LED TSUS5400	0.176
Photodiode S186P	0.94
PIC 18F2525	5.71
All Capacitors	2
Oscilator	2.18

7.5.3 Test Bench and Measurement Results

Our main problem when taking the turbidity measurements was to determine the turbidity level of each solution test probe. These values were necessary in order to estimate the analytical model of our system. This section explains the process carried out to take the measurements and the calibration process of our system.

7.5.3.1 Used elements

On the one hand, we employed a calibrated turbidimeter to know the accurate value of turbidity of each test probe to be measured. The used device is Turbidimeter Hach 2100N. This turbidimeter can take measurements in two modes (ratio mode and non-ratio mode). We have used the non-ratio mode, which measures the turbidity by using a detector placed at 90 degrees.

All measures have been performed for seawater. The salinity of the sea water depends on the geographic position. Our samples were taken from the east coast of the Mediterranean Sea (Spain). The average water salinity ranges from 36 to 38 grams per liter. pH is 8.07 and its temperature is 21.1ºC.

Regarding to the elements used to generate the dissolutions with different turbidities, we have used a mixture of clay and silt. The silt is a loose material with a grain size between fine sand and clay. It is incoherent classic sediment transported in suspension by rivers. The particle size of our sample is between 0.002 mm and 0.06 mm.

The glass containers used in our test had a volume of 30ml.

First, took four calibration samples in the turbidimeter Hach 2100N. Then, we took 10 samples with turbidities. Next, we performed more samples at lower concentrations than at higher ones because lower concentrations are most usual. The concentration samples we prepared are shown in Table 7.3.

Table 7.3. Samples, their concentration and turbidity

Sample	Samples and Their Concentration		
	Amount of clay and silt added (g)	Concentration (mg/l)	Turbidity (NTU)
1	0	0	0.072
2	0.00109	36.33	23.7
3	0.00301	100.33	50.8
4	0.00331	110.44	60.1
5	0.00526	175.33	97.2
6	0.00696	232.10	123
7	0.00782	260.66	142
8	0.00980	326.66	171
9	0.01821	607	385
10	0.0453	1512.59	785

Figure 7.14 shows the relationship between the amount of solute and the concentration of the test probe.

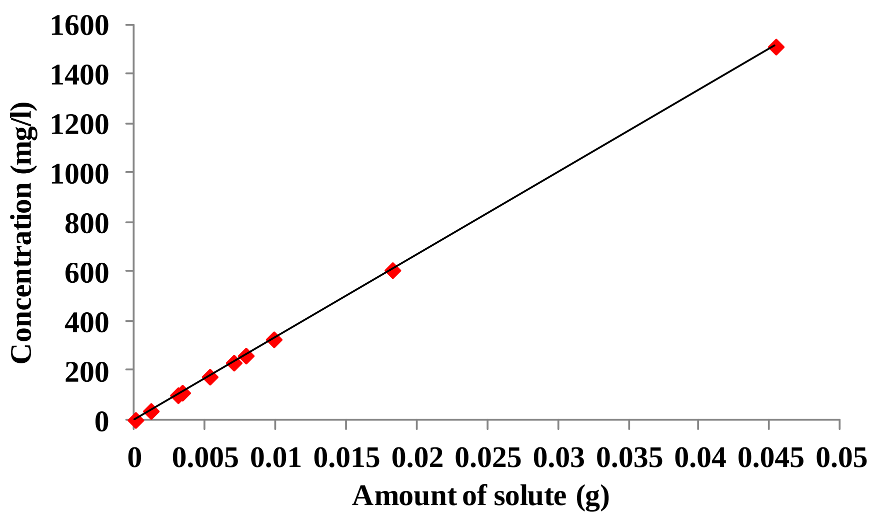

Figure 7.14. Value of dissolution turbidity as a function of the dissolution concentration.

We can extract the relationship between both values using Equation 7.8 with a correlation coefficient of 0.9999. Because the independent term is extremely small value, we can approximate this relationship without take into account the independent term.

$$C = 33.333 \cdot S + 10^{-13} \cong 33.333 \cdot S \tag{7.8}$$

Where C represents the concentration of the dissolution in mg/l and S represents the amount of solute in g..

Each prepared sample has a turbidity value. Figure 7.15 shows the relationship between the concentration of silt-clay in seawater and the water turbidity value.

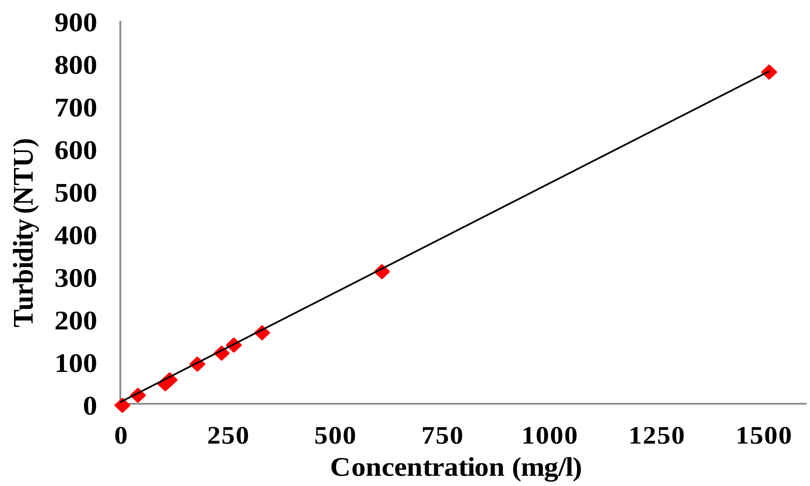

Figure 7.15. Value of dissolution concentration as a function of the amount of solute.

Equation 7.9 shows the relationship between both parameters with a correlation coefficient of 0.9999.

$$T = 0.517 \cdot C + 3.0027 \tag{7.9}$$

Where, T represents the turbidity in NTU and C is the dissolution concentration in mg/l.

Finally, we can express the turbidity as a function of the amount of clay-silt dissolved combining Equation 7.8 and Equation 7.9. It is given by Equation 7.10.

$$T = 17233.161 \cdot S + 3.0027 \tag{7.10}$$

Where, T represents the turbidity in NTU and S, the amount of solute in g.

7.5.3.2 Obtained results

After measuring the turbidity of each sample, we placed each one in our system in order to measure their voltage values.

Figure 7.16 shows the gathered output voltage value for each value of turbidity. The prepared samples are shown in red while the standard samples are shown in blue. We have also add, in black, our mathematical model extracted by Equation 7.11. We can see that the behavior of our system is not linear. Its behavior can be approximated to a linear function up to turbidity values of 300 NTU. But for higher turbidity values, the behavior is closer to a curve function.

Using these 14 samples, we have estimated the analytical expression that models the behavior of our turbidity sensor. Our system is modeled following Equation 7.11, where, x represents the independent term and y the represents the dependent value.

$$y = a + \frac{b}{(c + x + d \cdot \sin(e + f \cdot x) + g * \cos(h + i \cdot \sin(j + k \cdot x)))} \tag{7.11}$$

We used Eureqa Formulize [358] to estimate the analytical model. Equation 7.12 relates the turbidity with the output voltage of our system.

$$y = 0.9767 + \frac{1550}{(353.4 + x + 31.69 \cdot sin(5.435 + 2.004 \cdot x) + 19.34 * cos(6.141 + 18.85 \cdot sin(5.443 + 2.004 \cdot x)))} \tag{7.12}$$

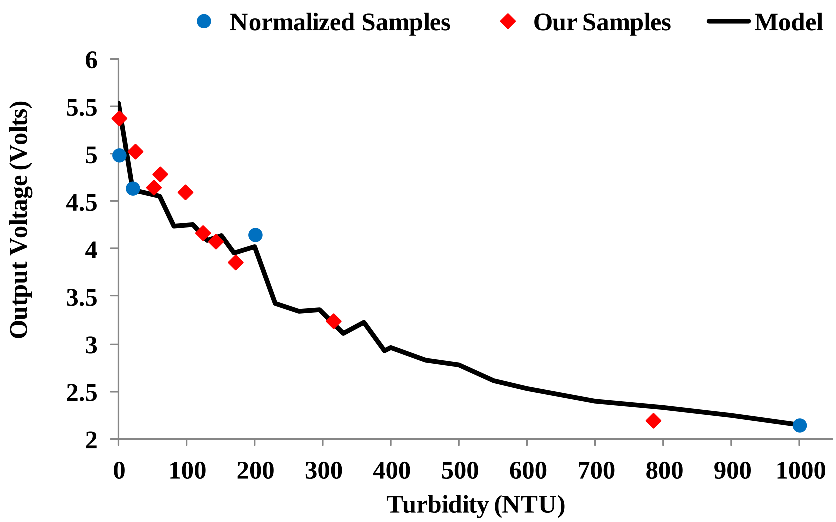

Figure 7.16. Output voltage as a function of the turbidity value and our mathematical model.

Finally, in order to check the accuracy of our system, we represent the output voltage value predicted by our model versus the value of output voltage obtained by our system. Figure 7.17 shows this relation. As Figure18 shows, most points remain in the black line which indicates a perfect match.

From Equation 7.12 and Figure 7.17, we observe that our equation has a correlation coefficient of 0.99897 and its maximum error is 0.1 Volts.

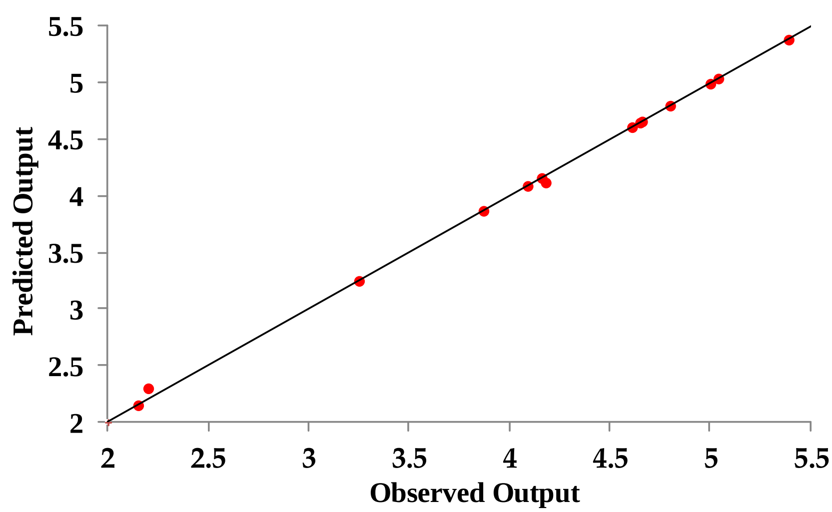

Figure 7.17. Observed output vs. Predicted output

7.5.3.3 Verification

In order to test the accuracy of our system, we have compared the values obtained by the turbidimeter Hach 2100N and the values obtained by our turbidity sensor.

In the verification test, we have chosen low concentration samples, which means low turbidity. In these situations it is more difficult to measure accurately the turbidity. Commercial Turbidimeters have also problems in low turbidities. In order to perform this step, we have prepared four samples with unknown concentrations. The output voltages obtained for each sample are shown in Table 7.4.

Table 7.4. Unknown samples.

Samples	Samples to verify			
	1	*2*	*3*	*4*
Output Votlage	4.67 V	4.82 V	4.80 V	4.33 V

Estimating the turbidity values by using Equation 7.12, we have introduced our samples (in blue) in Figure 7.18. It shows the behavior of our system.

In order to compare the estimated turbidity values with the measured values and the error for the four samples, we provide Table 7.5.

Table 7.5. Verification results.

Results	Samples to verify			
	1	*2*	*3*	*4*
Turbidity obtained	73.66	55.36	57.80	115.2
Turbidity (Hach 2100N)	70	54.8	59	129
Error in Turbidity (%)	5.22	1.03	2.03	10.75

The biggest error in turbidity is registered for the fourth sample (10.75 %) meanwhile the samples with lower turbidity present an error of 1.03 %.

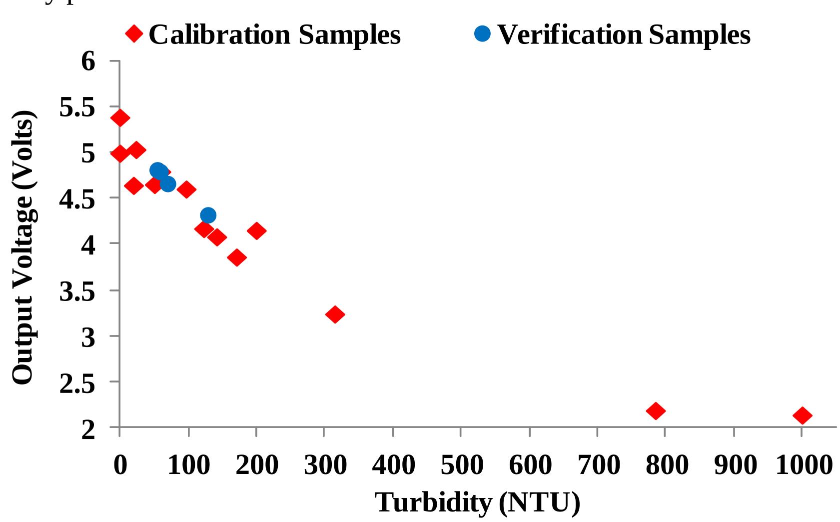

Figure 7.18. Output voltage value for the verification samples

7.6. Fish Feeding Simulation

Finally, we are going to show a simulation where we compare the amount of food that is thrown into the water in a regular process and the estimation of amount of food thrown into the water, if our system was used. We will also see the amount of pellets which are deposited on the seabed for both systems.

A regular feed dispenser can feed from just a few grams of pellets every second up to 200-300 grams per second. On-growing fish farm systems are delivered with the capacity up to 3 kg per second. They can feed up to 45 tons each hour. The bigger on-growing systems can dispense between 10 kg and 3 tons every hour [381].

In order to simulate our system, we have supposed two marine fish cage (biomass of 2.800 kilograms inside) in the Mediterranean zone. The first one contains Sparus aurata and the second cage contains Dicentrarchus labrax. We simulate two situations. The first one is the process of fish feeding in summer season with a temperature range of 24.5°C - 26.5°C. The second situation is the process of fish feeding during winter season with a temperature range on 12°C – 13°C. We have compared the process feeding for our system and for a regular procedure.

To do it, we have used Octave [382] which is a high-level language created for numerical computations.

We should note that the fishes are fed during 75 minutes in summer while in winter, this process takes 45 minutes.

Figure 7.19 shows the system performance for regular procedure during the seasons of summer and winter for both the Sparus aurata and the Dicentrarchus labrax. In a regular procedure in summer season, the Sparus aurata eats more than in winter season. In summer, they get to eat 3 tons of pellets each time (approximately 667 grams per second) while in winter, the Sparus aurata needs to eat approximately 500 kilograms (about 185 grams per second). In summer, the Dicentrarchus labrax usually eats a mean of 2.5 tons of pellets (approximately 556 grams per second) meanwhile this specie eats around 600 Kilograms each time (approximately 222 grams per second). As we can see all feeding processes are similar and they maintain these values during all process.

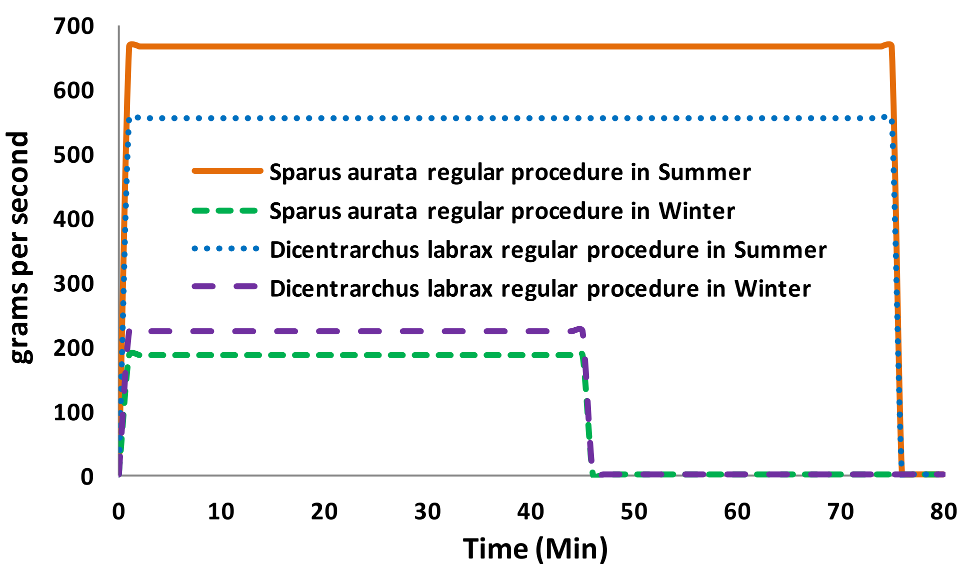

Figure 7.19. System performance for regular procedure in winter and summer.

Figure 7.20 shows the system performance for our system during the seasons of summer and winter for both the Sparus aurata and the Dicentrarchus labrax. In our case, the amount of pellets per second is the same for both seasons. We can see that the behaviour is the identical for the four cases. In summer season, both the Sparus aurata and the Dicentrarchus labrax eat constantly during 65 minute. In this moment, our system detects enough biomass moved to the bottom (although there are some fishes satisfied before). Our system changes its dispensing speed to a slower speed. This behavior is also repeated at 72 minutes. Finally at 79 minutes our system stops the dispenser

During the winter season, both species eat fewer amounts of pellets. The system behaviour is the same as the one explained before. At 30 minutes the system detects enough biomass moved to the bottom, so, our system changes its dispensing speed to a slower speed. This behaviour is also repeated at 38 minutes. Finally, at 45 minutes our system stops the dispenser.

We can see that our feeding process changes the feeding speed of the dispenser as the fishes are satisfied. This implies the saving of more food.

Pellets can be found in many different sizes; from tiny ones (around 2 mm in diameter) to big ones (around 28 mm of diameter). Both Sparus aurata and Dicentrarchus labrax usually eat 6mm-6.5mm pellets when they have a weight of 500 grams. A regular pellet with this size has a mean weight of 0.5 grams.

Figure 7.21 shows the number of pellets that have fallen to the seabed for both species during a regular procedure management feeding process (using a table with time values or observing that there are no hungry fishes on the surface) during summer and winter seasons. We can see that the most amounts on pellets are concentrated at the end of the feeding process.

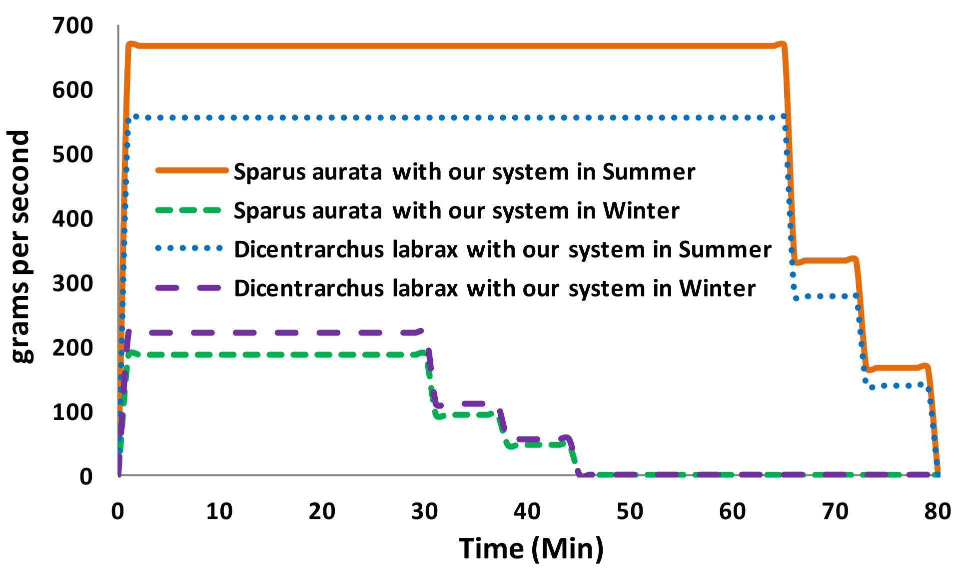

Figure 7.20. System performance for our system in winter and summer.

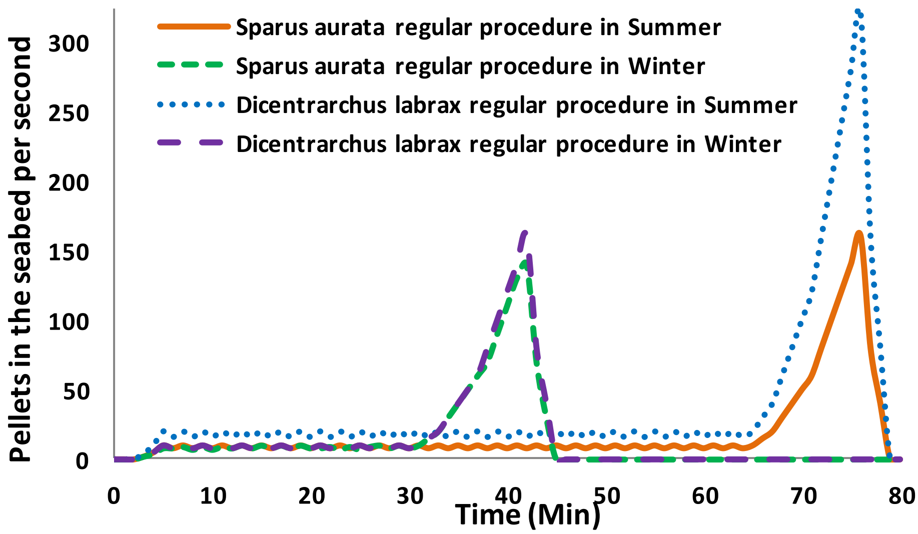

Figure 7.21. Pellets in the seabed for a regular procedure in winter and summer.

Figure 7.22 shows the number of pellets which have fallen to the seabed for both species during our automatic management feeding process in summer and winter seasons (using a table with time values or observing that there are no hungry fishes on the surface). We can compare the behaviour of our system with the behaviour of a regular process (Figure 7.21) and it is easy to see that fewer pellets fell to the seabed in our proposal. We can see that at the end of the feeding process the difference of the number of pellets in the seabed is substantially lower.

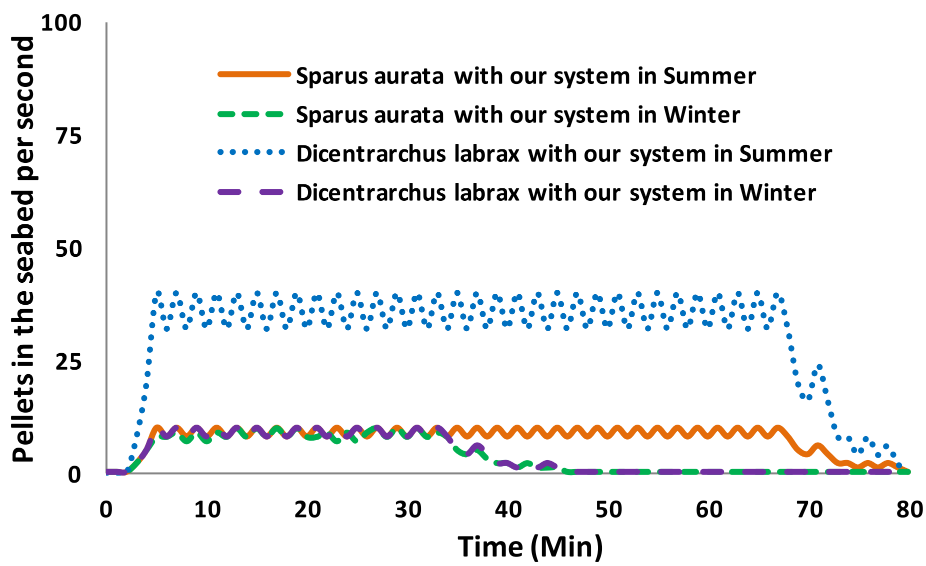

Figure 7.22. Pellets in the seabed for our system in winter and summer.

7.7 Conclusion

In this chapter, we have seen that one of the most important problems in regards to sustainability in marine fish farms is the economical losses and environmental impact generated by the faecal pellets and uneaten feeds sprawling under the cages.

In this chapter, we have presented a system in order to monitor and control the process of fish feeding in marine fish farms. Our system is based on group of several sensors which control parameters such as depth under the cage, the mean current speed, the current direction, the settling speed, the position of each cage and the physic-chemical characterization of the water and water pollution, among others.

Our simulation shows that the system reduces the problem of wasted food, its economic losses and, furthermore, decreases the environmental impact. Moreover, the number of people controlling the feeding process is reduced because it is controlled automatically.

In addition, this chapter shows the deployment of two low cost oceanographic sensors. The first ones are based on an optical sensor and it is used to detect the amount of depositions in the seabed. The second sensor is a turbidity sensor which can help us to determine the quality of water. The most notable characteristic of both developments is its low manufacturing cost. While commercial sensors for oceanography can cost more than 2000 - 3000 €, we are developing systems with much lower costs.

We can conclude that the development of low cost sensors can be possible and their application to the marine fish farms suppose a big economical cost regarding to the maintenance costs and a reduction on the environmental impact on surrounding areas.

Now, we are developing other oceanographic sensors taking in to account several energy constrictions to deploy them in a real fish farm. Future works will show the difference between our estimations and the real measurements using our sensors.

Finally, work presented in this chapter has been published in the following references [178], [179] and [180].

Chapter 8

Conclusion

8.1 Introduction

The implementation of a sensor network must always be preceded by an analysis of the problems presented in the environment. This process will give us the information about the sensing type we should perform the kind of devices we want to develop and the performance which can be obtained depending on the type of technology we use.

As we have seen in this dissertation, the scope of the WSN is very wide and sensor nodes share many characteristics. The first is that when we are working in natural environments the main problem we have, is the limitations of energy. This problem can be treated from different points of view. Maybe, the most important one is the hardware used to implement the node. We can also reduce the energy consumption of network using groups-based topology networks where the amount of routing information between groups and nodes is much lower than the information exchanged on a regular ad-hoc topology. Finally, the choice of an optimized communication protocols that take into account the amount of power remaining in the node to route the information another way, could help us to reduce the global energy consumption.

Because this kind of network uses wireless communication technologies, once defined the environment where the node will work and the type of device used, it is important to determine the transmission loss due to vegetation, reflections, refractions, hostility of medium, etc. This will give us an idea of the number of nodes we need to monitor an area and the type of design for our network. This will also define the most appropriate technology.

Finally, we should implement our proposals and verify its operation.

This chapter presents the main conclusions of this Thesis and presents possible future research lines.

Because at the end of each chapter, we have presented the summaries and main conclusion about the proposals and measurements performed in each chapter, in this chapter, we are going to present these conclusions from a wider and global perspective.

8.2 Conclusion and Contributions

Throughout this dissertation we have seen the improvements provided by each of our proposals and deployments. In this section we are going to show a summary about every contribution performed on behalf this Doctoral Thesis.

In this dissertation, we have presented the main features and requirements of a wireless sensor node and a selection of the most used commercial wireless nodes. We have also presented the main issue which can be found in nodes and have defined the analytical expression of energy consumption in wireless nodes in function of the amount of information transmitted.

We have checked that network topologies based on group made fewer packet retransmissions, compared to the traffic generated in a network using common protocols such as AODV, DSDV or DRS. This reduction of packets is translated in to a considerable energy savings.

Regarding to WSN for environment monitoring, we have been seen that it is possible to develop several kinds of networks to apply them to any environment. We only need to specify the problem and the measurable parameters.

We would like also highlight the practical studies of the wireless signal behavior of IEEE 802.11a/b/g/n. From the results of the scenarios analyzed we have proposed a new method for the positioning of wireless sensor nodes, which reduces in 15% the number of nodes required to cover an area. Unlike the already existing models, our method only requires as input parameters, the size of the building and the transmission power of access point. Reducing the number of sensor nodes is important when we want to completely cover a given area. The smaller the number of nodes, the lower energy and economic costs will have the network.

Related to underwater environment, we have analyzed the performance of underwater communications in fresh water and its dependence on the working frequency and temperature. As we have seen at the end of Chapter 6, several previous works had performed erroneous theoretical estimations in regards to this type of communication. So far, we are working with distances of 26 cm, but we are investigating ways to increase this distance. The main findings after performing all these tests it is possible to extract a combination of transmission parameters as a function of temperature.

Finally, we have proposed the use of a network of groups of sensors for monitoring and controlling the process of fish feeding. Just as people, fishes change their activity according to their level of satiety. Therefore, it seemed obvious to link the amount of food thrown to the fish with the activity and behavior of these.

The latest figures of Chapter 7 show that using our sensor network, we could reduce food thrown to the cages in a 23% compared to the food used in a regular procedure. Further, we would reduce by almost 10% the amount of food deposited in the seabed.

Regarding the development of sensors, as we have seen in the case of turbidity sensor, the implementation of a sensor is not as expensive as we think. With a careful design, we can develop sensors for a few tens of Euros while its market price can exceed several thousands of Euros.

From the work performed in this Thesis, we have published 28 papers. All of them are directly or partially related to the presented work. Seven of these publications have been presented in international conferences and four of them are chapters in research books. The rest belong to international journals publications where eleven of them have Impact Factor (JCR) of ISI Thomson.

Last contributions and participations have been related to the inclusion of network security mechanisms [383]. As a future work, we would like to add the most suitable security mechanisms for each network in order to prevent any attack to the network and data corruption.

8.3 Future Work and Research Lines

Following the ideas and proposals presented in this dissertation, we can propose different futures projects to continue this investigation. Because underwater wireless communications based on the EM waves are still poorly investigated, most of these new ideas would be for underwater applications.

The first improvement we would like to provide to our developments, especially for underwater sensors (although it is applicable to other devices) is the use of the energy harvesting from other sources to provide energy to our devices. In this way, we would increase the network lifetime reducing the maintenance costs of devices.

Given in mind that underwater freshwater communications depend on several factors, such as temperature, operating frequency and transfer rates, we would like to design and develop an intelligent node. The node would be able to adapt its transmission conditions depending on water conditions. It would be able to switch between the transmission parameters and communicate their state to its neighboring nodes, to optimize the transmission between them. With the development of this node, we would also like to design a more efficient antenna underwater environment. We have not found any model that meets these characteristics. Finally, we would like to move all these tests at seawater, because the final goal it to apply these as if the aim is the application of marine farms.

Finally, we continue working on the development of low cost efficient sensor nodes for rural and underwater environments. We believe that, just as we have done with the turbidimeter, we can design and develop multiple devices with much lower costs than current ones without reducing their accuracy.

We are confident that the use of these sensors will provide significant cost savings and improved sustainability for marine farms.

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