engineering proceedings

Proceeding Paper

Bridging the Gap: Challenges and Opportunities of IoT and Wireless Sensor Networks in Marine Environmental Monitoring †

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† Presented at the 10th International Electronic Conference on Sensors and Applications (ECSA-10), 15–30 November 2023; Available online: https://ecsa-10.sciforum.net/.

Abstract: Marine environmental monitoring is increasingly vital due to climate change and the emerging Blue Economy. Advanced Information and Communication Technologies (ICTs) have been applied to develop marine monitoring systems, with the Internet of Things (IoT) playing a growing role. Wireless Sensor Networks (WSNs) are crucial for IoT implementation in the marine realm but face challenges like modeling, energy supply, and limited deployment compared to land-based applications. This paper explores various communication technologies, considering factors like coverage, cost, energy use, and stability. It highlights the potential of wireless technology in marine conservation and activities like port operations, aquaculture, and renewable energy, offering insights from real-world testing in the Region of Murcia.

Keywords: marine environmental monitoring; marine internet of things (MIoT); wireless sensor networks (WSNs); communication technologies in marine environment; blue economy

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Citation: Errachdi, H.; Felis, I.; Madrid, E.; Martínez, R. Bridging the Gap: Challenges and Opportunities of IoT and Wireless Sensor Networks in Marine Environmental Monitoring. *Eng. Proc.* **2023**, *58*, 102. https://doi.org/10.3390/ecsa-10-16158

Academic Editor: Stefano Mariani

Published: 15 November 2023

1. Introduction

Marine environmental monitoring has garnered increasing attention due to mounting concerns regarding climate change and the burgeoning Blue Economy, which acknowledges oceans and seas as economic drivers. Over the past two decades, advanced Information and Communication Technologies (ICTs) have been applied to develop monitoring systems for the marine environment and its anthropogenic activities. In this context, the Internet of Things (IoT) is progressively demonstrating its role. The IoT offers data processing capabilities, enabling intelligent object control and the agile development of applications aligning with biodiversity conservation and economic growth.

A pivotal technology for IoT implementation is Wireless Sensor Networks (WSNs), comprising autonomous devices distributed across an area of interest to monitor physical or environmental parameters. However, the application of the IoT in the marine environment remains distant from realization, and the utilization of WSNs in this context is constrained by issues like modeling, energy supply, range, and bandwidth. In fact, deployments of these technologies in the marine environment lag significantly behind their terrestrial counterparts. Furthermore, a comprehensive and contextualized examination of wireless communication technologies in the marine environment is still lacking.

Hence, this text presents an exploration of various communication technologies (Bluetooth, ZigBee, WiFi, WiMax, LoRa, LoRaWAN, SigmaFox, GSM, 3G, 4G, etc.), considering spatial coverage, deployment and maintenance costs, energy consumption, stability, data throughput, and more. This study, utilizing the coastal telecom stations in the Region of Murcia (Spain) as a pilot application area, focuses on the opportunities wireless technologies offer for marine conservation and the sustainable development of activities such as port operations, aquaculture, fishing, offshore renewable energy, and autonomous risk mitigation vehicles.

Additionally, the project conducts systematic tests of these communications by deploying WSN nodes at various distances and data rates to simulate real marine activities, employing advanced data compression techniques to enhance data transmission. The results provide invaluable insights for the future deployment of wireless communication technologies in the marine environment, promoting both environmental preservation and the sustainable advancement of marine-related activities.

2. Challenges and State of the Art

2.1. Challenges of WSNs in the Marine Environment

In recent decades, there has been an increase in the number of technological solutions based on Wireless Sensor Networks (WSNs), which have a series of advantages in monitoring the environment, its biodiversity, and the activities that take place in it, such as autonomous operation, real-time supervision (reducing effort and staff hours), and relatively low cost [1]. In fact, the costs derived from the use of these monitoring technologies are being reduced, thus making them cost-effective tools compared to traditional forms of monitoring [2].

However, the current protocols and design specifications of land-based WSNs must be adapted to the requirements of the marine environment [3], making their deployment in the marine environment a challenge [4]. In this sense, the development of WSNs in the marine environment presents obstacles related, on the one hand, to the capacity and time needed to store, share, and analyze the large volumes of data that must be managed through communication networks and, on the other hand, the limited resources that we find in the marine context itself, in particular, self-sufficient power supply, data storage capacity, and communication bandwidth [5]. These obstacles are considered one of the largest challenges in the design of automated stations for monitoring the marine environment.

Regarding the large volume of data in the marine environment, it should be noted that, in addition, marine traffic has been growing considerably in recent years [6], as well as the number of monitoring systems necessary for the navigation and monitoring of vessels, which means that the data obtained have increased to the same extent and are susceptible to integration into a network [7].

Regarding the challenges posed by the marine context itself, we find different studies focused, among others, on energy storage beyond conventional batteries that require a high level of replacement [8], renewable energy supplies adapted to WSNs [9], the impact of sea waves on the propagation of communications and the quality of the communications link [10], and the effect of the ocean environment for cellular IoT [11,12].

For all these reasons, new techniques and algorithms must be addressed to achieve this goal, from the scope of the sensors and nodes of the network, and the network architecture itself, to the protocols and network technology used [13].

2.2. Application of Existing WSNs to the Marine Environment

An IoT-based protection and monitoring system is composed of five layers [14]: the perception and execution layer, the transmission layer, the data preprocessing layer, the application layer, and the business layer.

The network/transmission layer is the most important layer in IoT architecture, as a variety of devices (switches, hubs, compute performance, gateways, etc.) and different communication technologies (ZigBee, Bluetooth, LTE, 5G, 6LoWPAN, Wi-Fi, etc.) are combined in this layer [15]. The network layer must provide data to or from different objects or applications, through gateways or interfaces between heterogeneous networks, and use different communication technologies and protocols.

The application of these technologies depends on the distance to be considered and the volume of data to be transmitted. For example, to exchange data in a communication at a short distance (~100 m), NFC, ZigBee, and Bluetooth could be a good choice; for medium-distance communication (~0.1–1 km), we could use WiFi; while for long distance (>1 km), the most promising technologies would be LTE, LTE-A, WiMAX, and LoRaWan (LoRa).

Near the coast and in port environments, 3G, 4G, and, in the near-future, 5G coverage is excellent thanks to the proximity of the antennas. Likewise, there are protocols such as NB-IoT (Narrowband Internet of Things) specifically designed to interconnect IoT devices on LTE technologies.

In order to give as complete a picture as possible of the efforts made to date in the implementation of communication networks in the marine environment, a bibliographic search has been carried out, from which two key characteristics can be extracted: name of the technology and protocol, distance between transmitting and receiving antenna, and communication data throughput, as well as other relevant information such as consumption, frequency, and ultimate application.

In this search, 72 articles have been found that address this problem from an empirical point of view. Most of the 72 articles collected were extracted from two reviews by Xu et al. and Sung-Woong [16]. The rest have been obtained by carrying out alternative and specific searches. However, from all these articles, we cannot extract all the key data defined above. This circumstance leads to the fact that this information is not easily found, and even less so in a technology-specific way, in the same article. However, they do give us a global idea of which technologies are most tested in the marine environment.

Of these 72 articles, we can see that 13 articles use radio-based communication technology, 7 use ZigBee technology, 7 use Wi-Fi communication protocols but applied to other technologies such as LTE to achieve greater range, 4 use 4G technology, 6 use 2G technologies, and the rest of the technologies have been used much less. It should be noted that, for technologies such as 3G or SigFox, no studies have been found applied in the marine environment where the flow and range are empirically verified and specified. On the other hand, 21 articles do not specify enough information about the communication technology that has been installed to collect the data in the current state of the art.

However, only 20 relevant applications are extracted from the tested wireless communications, in which we find explicit information regarding the flow and range of the communication. The following shows the feature set of these 20 experiments (Table 1):

Table 1. List of technologies tested at sea according to the bibliographic search, in which we find explicit information regarding the flow and range of communication.

Author	Year	Country	Technology	Range (m)	Caudal (kbps)	Cost
Singapore Gov. [17]	2007	Singapore	WiMAX	15,000	5000	Middle
Mi.-T. Zhou et al. [18]	2013	Japan	WiMAX	14,200	6000	Middle
M.-T. Zhou et al. [18]	2013	Japan	WiMAX	8660	6000	Middle
H.-J. Kim et al. [19]	2015	Korea	LTE	10,000	7600	Middle
H.-J. Kim et al. [19]	2015	Korea	WLAN	20,000	4700	Middle
J. M. Almeida et al. [20]	2016	Portugal	LTE	30,000	5000	Middle
J. M. Almeida et al. [20]	2016	Portugal	Wi-Fi	60,000	3200	Middle
Sethuraman et al. [21]	2018	India	LR Wi-Fi	52,000	3000	Low
Sethuraman et al. [21]	2018	India	LR Wi-Fi	22,600	3000	Low
M. Höyhtyä [22]	2017	Finland	Wi-Fi	900	27,000	-
S-W, Jo [16]	2019	Corea	LTE	107,000	12,000	-
G. Kazdaridis [23]	2017	Serbia	LoRa	21,000	50	-
C. De Marziani et al. [24]	2011	Spain	ZigBee	1200	250	-
Silva L.G. [25]	2013	Argentina	WiFi	16,000	64,000	-
S. Jiang et al. [26]	2015	China	MF/HF	463,000	0.1	-
S. Jiang et al. [26]	2015	China	VHF	120,000	1.2	-
S. Jiang et al. [26]	2015	China	VHF	120,000	9.6	-

Table 1. *Cont.*

Author	Year	Country	Technology	Range (m)	Caudal (kbps)	Cost
S. Jiang et al. [26]	2015	China	MF	556,000	18	-
S. Jiang et al. [26]	2015	China	VHF	120,000	307	-
Marlaski et al. [27]	2018	Denmark	NB-IoT	3439	66.7	-

The following graph shows the scope of the communications used in these publications, taking into account both the distance and the data throughput tested in the different experiments.

It is observed that radio frequency is one of the most used technologies as it has a range well above the average, exceeding 100 km, but with a somewhat limited capacity to transmit data, and whose implementation cost will depend on the base stations that exist. However, there are studies where 4G technology has been implemented for the same distances, but with a substantially higher throughput. On the other hand, there is an area where the use of technologies such as WiFi (but combined with other technologies to achieve these long ranges), WiMAX, LTE (4G), and RF converge for a range of more than 10 km with a data flow between 103 and 104 kbps. Finally, although there are not much data on the range and flow used with ZigBee technology, its use is widespread and, based on the experimental data collected, it can be seen that it has a considerable range, although the data flow would be low, not exceeding 102 kbps at such distances.

With this, the present work aims to test different technologies that allow communications between coastal activities, resource extraction activities, and off-shore renewable energy platforms, among other land-based activities using communication technologies in Figure 1, covering areas that have not been covered in this graph both in bandwidth and distance.

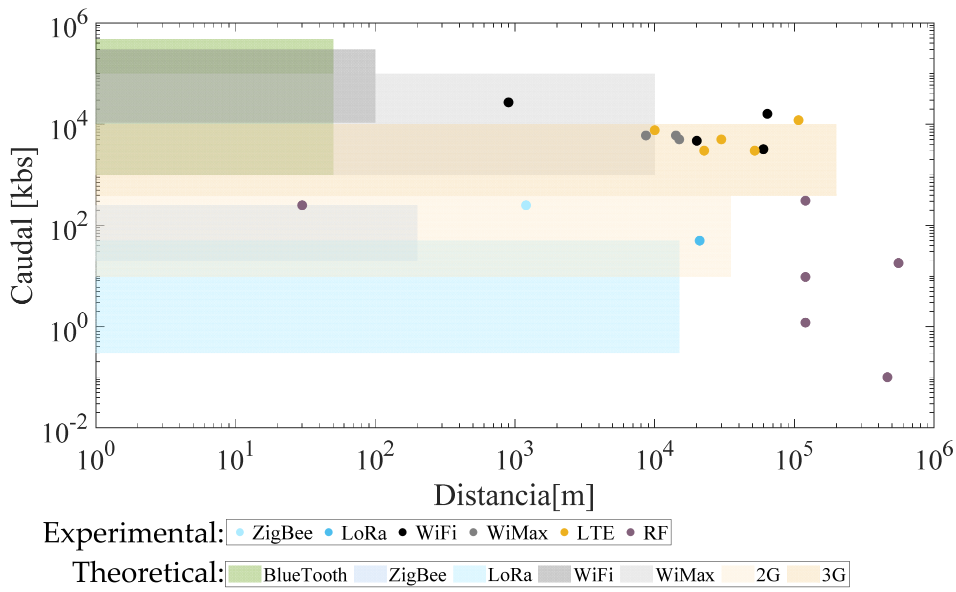

Figure 1. Comparison between distance and expected data throughput for different communications (shading) with respect to experimental results from the literature (points) (authors' own creation).

3. Materials and Methods

This research aims to investigate the limitations of existing wireless communication technologies for the development of Wireless Sensor Networks (WSNs) in the marine environment. This study encompasses both theoretical analysis and experimental deployment, focusing on supporting strategies for the sustainable conservation and exploitation of oceans and seas. The coastal regions of the Region of Murcia serve as the practical application area for this research endeavor. In order to achieve this objective, the following specific methods are outlined:

- To compare different electromagnetic communication propagation simulation techniques that account for the specific circumstances and scenarios in the marine environment.
- To test the development and deployment of different communication technologies at varying distances from the coast, data throughput rates, and consumption requirements, addressing real needs in marine contexts and activities.

To fulfill these specific objectives, a combination of theoretical work, involving a literature review within this report and previous experience from the CTN, and experimental work for technological development and technology deployment in the marine environment is conducted.

3.1. Electromagnetic Propagation Simulation in Marine Environments

In this section, we delve into the theoretical study of modeling propagation losses associated with the transmission of electromagnetic waves at typical frequencies used in radiocommunications. Based on this, algorithms of varying complexity are implemented to enable the exploration of more realistic studies.

3.1.1. One-Ray Model (Free-Space Propagation Model)

This model considers a characteristic free-space propagation model, which does not take into account any form of reflection, refraction, or any other scattering mechanism of the beam. It is analogous to a ray model, representing the direct path between the transmitter and receiver, making it the simplest model to consider. This model, also known as the Friis model, considers only losses due to the divergence of the wavefront, as reflected in its mathematical expression:

$$P_R/P_T = G_T G_R \left(\frac{c}{4\pi f l}\right)^2 \tag{1}$$

where G_T and G_R (P_R and P_T) are the gains (powers) of the transmitting and receiving antennas in the direction of the vector connecting them, respectively, separated by a distance l, and where f is the frequency of the electromagnetic wave considered (with c representing the speed of light).

More conveniently, in logarithmic scale, the propagation losses can be expressed as

$$L = 10log_{10}(P_T/P_R) = 20log_{10}(fl) - 10log_{10}(G_R G_T) + 20log_{10}(4\pi/c) \tag{2}$$

3.1.2. Two-Ray Model

In most cases, the previous model proves to be overly simplistic as it does not account for contributions from reflected rays. The two-ray model precisely takes into consideration the ray that, after being reflected by the ground (or another obstacle), also reaches the target, adding a contribution to the received field at the receiving antenna, as illustrated in Figure 2.

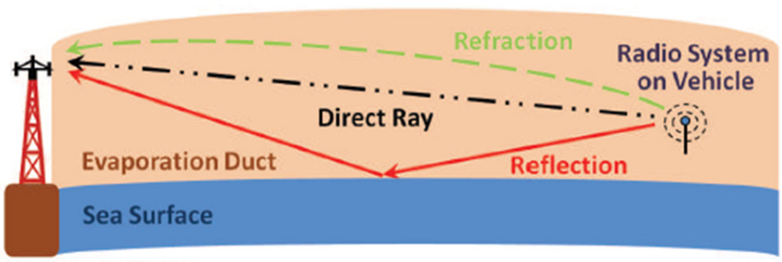

Figure 2. Raytracing corresponding to the different-number ray model.

This model extends the previous one by incorporating an additional term corresponding to the field generated by the reflected ray. In this case, the propagation losses are:

$$L = -20log_{10}\left(\frac{c}{4\pi f}\right)\left|\frac{e^{-ikl}}{l}\sqrt{G_T^d G_R^d} + R\frac{e^{-ikr_r}}{r_r}\sqrt{G_T^r G_R^r}\right| \tag{3}$$

where k is the wave number, r_r is the total distance covered by the reflected ray, and the superscript on the gain denotes the associated ray (d: direct; r: reflected). R is the reflection coefficient of the reflected ray, which depends on the angle of incidence, wave polarization, and electromagnetic characteristics of the involved media (air and water in this application).

In the literature, it is common to make the approximation of very small incidence angles, in which case the expression simplifies significantly. In particular, assuming a vertically polarized wave, it is obtained that the reflection coefficient $R = -1$ (phase changes by 180 degrees), which will be the default case in our scenario. However, we will continue to use this expression to account for the possible "roughness" of the sea, which will be discussed in more detail in Section 5, although its effects, given the long propagation distances and typical low antenna height(s), will be correspondingly minimal.

3.1.3. Three-Ray Model

The two-ray model is a good approximation to the problem at hand for short distances and under the specified conditions. However, it is widely recognized that for longer distances and depending on atmospheric conditions, there are discrepancies between what is observed and the analytical model. The main reason for this is the existence of a propagation channel formed by the presence of water vapor in the first few meters of air above the sea surface, which occurs under certain circumstances. In detail, when this vapor layer exists, it creates a minimum in the profile of the speed of light at altitude, causing the refraction of the beam and leading to a third ray reaching the target, as depicted in Figure 2. According to the literature, this effect appears in channels spanning distances greater than 5 or 6 km. The significance of this effect is that it causes "valleys" of losses and significant "peaks" in gain from distances of this order of magnitude onward.

Although the refracted ray is not reflected at any point, for analytical simplicity, it is assumed to behave as if it were reflected, at a certain effective height approximated as the duct height. In conclusion, the three-ray model follows the following equation:

$$L = -20log_{10}\left(\frac{c}{4\pi f}\right)\left|\frac{e^{-ikl}}{l}\sqrt{G_T^d G_R^d} + R\frac{e^{-ikr_r}}{r_r}\sqrt{G_T^r G_R^r} + \frac{e^{-ikr_{rf}}}{r_{rf}}\sqrt{G_T^{rf} G_R^{rf}}\right| \tag{4}$$

where r_{rf} is the distance traveled by the refracted ray, which can be calculated using the following expression:

$$r_{rf} = r_{rf1} + r_{rf2} = \sqrt{(h_e - h_t)^2 + (h_t tan(\theta))^2} + \sqrt{(h_e - h_r)^2 + (h_r tan(\theta))^2} \tag{5}$$

where θ is the angle of incidence, h_e is the effective duct height, h_r is the height of the receiving antenna, and h_t is the height of the transmitting antenna. On the other hand, G_T^{rf} and G_R^{rf} are the gains of the transmitting and receiving antennas in the direction of the refracted ray, respectively. The duct height h_e can be determined using specific models. In this study, the Paulus–Jeske model [28] was implemented, which is the most referenced analytical model in the literature. This model uses air temperature, water surface temperature, relative humidity, and wind speed as input parameters to estimate the height of the evaporation duct.

3.1.4. Specific Models for Rough Seas

As seen earlier in the two- and three-ray models, one of the contributions to the (total) field at the receiving antenna comes from a ray reflected by the sea. While reflection can normally be assumed with an almost zero angle of incidence (θ), resulting in a reflection coefficient of −1 for vertically polarized waves, significantly simplifying the approach, in the general case, it must be included in the calculation.

There are generalizations beyond the ideal case of specular reflection, where the associated reflection coefficient can be described by the following equation:

$$R = \frac{sin\theta - Z}{sin\theta + Z} \tag{6}$$

where Z is the characteristic impedance of the reflecting medium (water in our case):

$$\mathrm{Z} = \begin{cases} \frac{1}{\widetilde{\varepsilon}_{\mathrm{r}}}\sqrt{\widetilde{\varepsilon}_{\mathrm{r}} - \cos^2\theta} \\ \sqrt{\widetilde{\varepsilon}_{\mathrm{r}} - \cos^2\theta} \end{cases} \tag{7}$$

with $\widetilde{\varepsilon}_r$ representing the complex relative permittivity of the medium.

In this context, when considering a rough surface rather than a smooth one, where reflections are more complicated to determine, it is common to use statistical models that characterize the surface in question and obtain, on average, an effective reflection coefficient. Thus, two different approaches have been implemented, each attributing different statistical properties to the sea surface height profile: the Ament approach and the Miller–Brown approach [29].

The Ament approach assumes that the heights of the sea surface are normally distributed such that

$$P_A(\xi; h_{rms}) = \frac{1}{\sqrt{2\pi}h_{rms}} e^{-\xi^2/2h_{rms}^2} \tag{8}$$

where h_{rms} is the root-mean-square deviation of sea surface height (of waves).

On the other hand, the more complex Miller–Brown approach considers the sea surface as a collection of sinusoidal waves with a uniform phase distribution, the expression of which is omitted here for brevity.

In summary, the roughness reduction factor is calculated as

$$\rho(k,\theta) = \int_{-\infty}^{\infty} e^{2ik\xi,sin\theta} P(\xi) d\xi, \tag{9}$$

When multiplied by the standard reflection coefficient, it yields the effective reflection coefficient ($R' = \rho R$).

Therefore, by introducing the expressions of Ament and Miller–Brown into this equation, we ultimately obtain the expressions for the effective reflection coefficients for the sea surface, which will need to be correspondingly included in the propagation loss equations.

3.2. Testing Communication Technologies for Coastal and Marine Needs

Different communication technologies can be used depending on the application. Two communication technologies used in this work are highlighted in green within the context of the wide range of existing technologies: LoRa for long-distance transmission with low bandwidth, and WiFi for transmitting data with higher bandwidth over short distances.

3.2.1. Test of the LoRa System

To ensure that the data reach the location where the gateway will be installed, tests were conducted around the boat's departure port days before conducting tests on the boat. In the map shown in Figure 3, the positions where coverage tests were conducted have been marked. In the yellow-marked positions (1 and 2), the data reached the gateway without any issues, while in the position marked in blue (position 4), there was no coverage, due to the presence of hills between the transmitter and the LoRa gateway.

(**a**) (**b**)

Figure 3. Tested LoRa coverage positions: (**a**) gateway position and remote points.; (**b**) photograph of the device at position 2.

3.2.2. Test of the WiFi System

On the one hand, a subsea noise node was deployed near the Faro de la Curra, at the entrance of the port, with an autonomous data acquisition system specifically implemented for signal recording, allowing for the modification of the recording time as needed. The WiFi transmitting antenna, OmniTIK 5ac, was connected to this system via an Ethernet cable. On the other hand, a receiving antenna with the same characteristics was placed at various distances from the transmitter, along the same dock, at distances from 100 to 500 m. Figure 4 shows the positions of the transmitter and receiver on the left and the receiving station with the receiving antenna and a recording PC on the right.

(**a**) (**b**)

Figure 4. Tested LoRa coverage positions: (**a**) gateway position and remote points; (**b**) photograph of the device at position 2.

3.2.3. Deployment of Lora and WiFi Systems in Real Off-Shore Marine Environment

The technologies (Wimax, Lora, and GSM) are employed to establish communications between a moving vessel and a terrestrial location, with the aim of maintaining seamless and continuous communication between these two points. Receiving antennas will be positioned on the coastline, while the vessel will follow a straight-line trajectory to ensure that the receiving antennas remain consistently within the same range as the transmitting antennas.

The initial deployment was carried out from the following location, with each technology's receivers prepared to receive data. In this deployment, the receiving equipment was positioned at a height of 6 m above sea level, with maximum effort dedicated to alignment and ensuring that it remained within the same range as the transmitters situated on the vessel. Testing is conducted until all technologies reach their maximum range.

The second deployment, at the subsequent location, is executed from a higher vantage point at 20 m above sea level to ensure a clear line of sight and minimize interference from the water's surface. The transmitter on the sea must be securely located and well mounted on the exterior of the vessel. Testing is conducted within a 20 km range for all three technologies (WIMAX, Lora, and GSM).

To carry out measurements in real environments, a boat trip was conducted in the waters of the Port of Cartagena.

4. Results

4.1. Theoretical Electromagnetic Propagation Simulation in Marine Environments

In this section, a comparison is made between the results provided by established tools from generic software and the models developed and described in the previous sections. Specifically, a test was conducted using Ubiquiti Networks' AirLink software for a hypothetical transect in the port of Cartagena.

The numerical comparison is shown in Figure 5, where good correspondence is observed between Ubiquiti Networks' software and the models implemented by the CTN. The largest discrepancy is noted with the three-ray model, which was expected as the tool does not account for the evaporation duct.

(**a**) (**b**) (**c**)

Figure 5. (**a**) Trajectory followed in the pilot study; (**b**) receiving antennas in this pilot; (**c**) transmitter antennas in this pilot.

Furthermore, in Figure 6, the results associated with a test using a higher height for the transmitting–receiving antenna (20 m) are provided. In this case, the correspondence between models and software is not as good as in the previous test, with discrepancies in parts of the simulation distance range (the best-matched zone is between 3 and 6 km). The slope of the curves from the ray models, particularly the two-ray model, aligns well with that produced by the reference software, although there is a slight offset between the two.

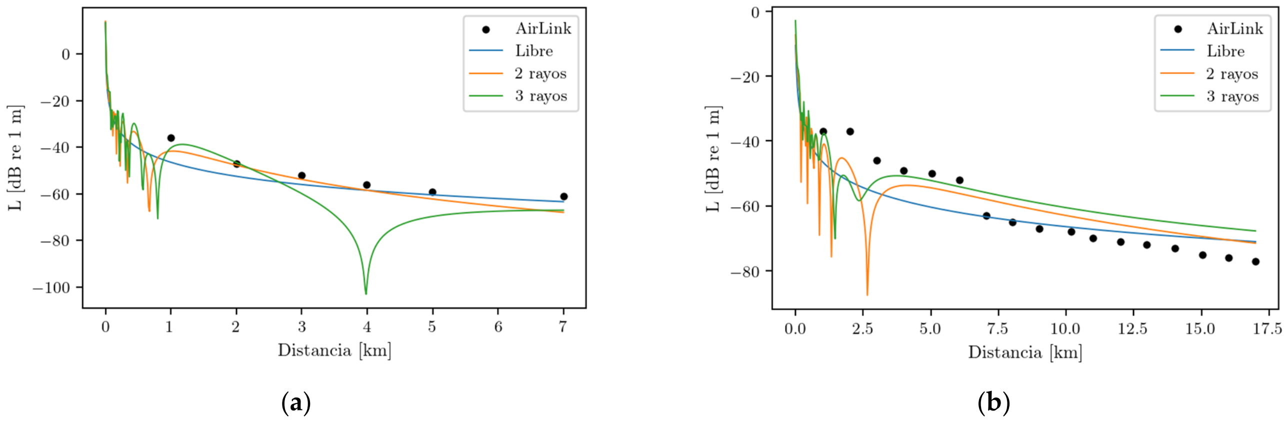

Figure 6. Comparison of results between propagation loss models and AirLink software for (**a**) first test; (**b**) second test.

4.2. Comparing Measures and Theoretical Propagation

In the first deployment, regarding WIMAX, it had achieved a straight-line range of 5000 m out to sea. Signal quality could have been further improved by deploying the receiving antenna at a higher point. Since the transmitting antenna on the vessel sent the WIMAX signal to the ground-based station, it was crucial to ensure that the antenna was stable and correctly oriented towards the base station. Any movement or change in the orientation of the transmitting antenna could have affected the signal quality sent and, consequently, the performance of the WIMAX connection.

In the second deployment, significant improvements in results were achieved, with a longer-range connection than in the first deployment. At this time, the receiving equipment was positioned at a higher location, providing greater visibility, reduced interference, and no obstacles in the environment that could have affected the signal. When testing for communication, the vessel was aligned as closely as possible with the receiver to remain within range and achieve a connection with a good transmission speed. In this test, the range of WIMAX was a success, reaching up to 14 km in a maritime environment.

In order to establish reliable data communication between the PC-powered Lopy1 device on a constantly transmitting vessel and the ground-based RAK724 receiving gateway at varying altitudes during the conducted deployments, continuous system monitoring was performed to ensure signal quality and reliability as each kilometer was advanced.

LoRa achieved a straight-line range of 6000 m out to sea, both in the initial deployment and in the subsequent one. Communication and range could be further enhanced by positioning the LoRa gateway at a higher point in the sea, increasing the effective transmitter height. This would enable the signal to reach greater distances while reducing the potential for interference and obstacles that could attenuate the signal. In general, elevating the antennas at both ends of the connection is considered the most effective means of improving range and signal quality.

As said, the experimental data were derived from the two campaigns conducted at sea, as detailed in the previous section. Specifically, data from the second sea campaign on 29 March 2023 were utilized. Figure 7 displays the results of this comparison.

As can be observed in Figure 7, there is a relatively good correspondence with the experimental data, especially concerning the two-ray model. Although it exhibits a difference of approximately 5 dB in the first 2 km, it closely replicates the data for longer distances. On the other hand, the free-space loss model underestimates losses for distances above approximately 8 km. Lastly, the three-ray model, which is more sensitive to input variables and exhibits more peaks and valleys, appears unsuitable for this case. One possible cause of this discrepancy may also be the low data resolution. If the data had been sampled more frequently, they might have captured those interference peaks and valleys in signal reception. This suggestion for improvement should be considered for future testing.

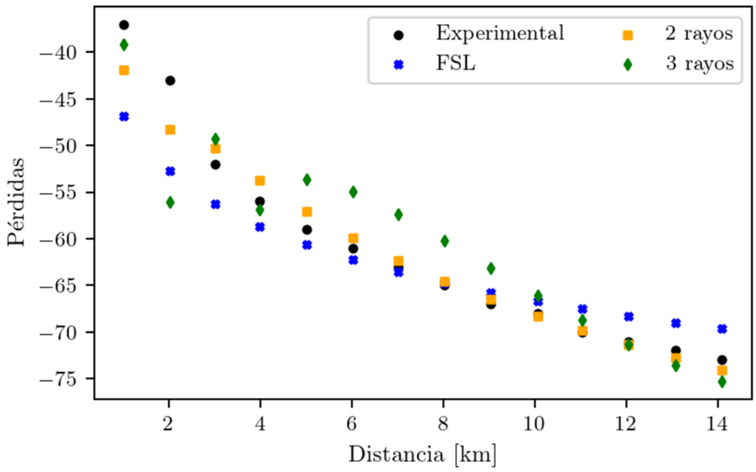

Figure 7. Comparison between experimental data (black circles) and those provided by the analytical models (remaining data).

5. Discussion

This study has addressed a set of significant challenges related to the implementation of wireless communication technologies in maritime environments, with a particular focus on the development of WSNs. We have thoroughly examined both the theoretical aspects and field tests in a real marine environment. Below, we discuss the findings and implications of this study.

One of the key highlights of this study is the identification and discussion of the major challenges faced in implementing WSNs in maritime environments. These challenges encompass the management of large volumes of data, the provision of sustainable power to sensor nodes, the limited data storage capacity, and the communication bandwidth. It is essential to note that these challenges are not merely technical but also logistical and economic in nature. The rising maritime traffic and the need to monitor and manage a variety of maritime activities such as navigation, fishing, and aquaculture demand effective solutions for data collection, transmission, and analysis. Our study underscores the significance of addressing these challenges as we move towards increased use of WSN technologies in the maritime domain.

We conducted a comprehensive evaluation of several wireless communication technologies in the maritime environment. This included technologies such as WiMAX and LoRa, with a focus on their range and data-carrying capacity. The results from our field tests demonstrated that different technologies have specific applications based on the distance and volume of data they need to transmit.

For instance, WiMAX tests revealed a range of up to 14 km in a maritime setting, making it a viable option for long-range communication in this context. LoRa, on the other hand, showed a range of up to 6 km, which is suitable for shorter-range applications but with adequate data capacity. These findings are valuable for making informed decisions on the selection of communication technologies in specific maritime projects.

A fundamental aspect of this study was the comparison between the results from our field tests and theoretical models of electromagnetic propagation. The models used included the free-space propagation model, the two-ray model, and the three-ray model. We observed that, in general, theoretical models provided a good match with experimental data, although significant discrepancies were noted at both short and long distances.

The two-ray and free-space models proved to be the most effective in describing the propagation conditions in our maritime environment. However, the three-ray model, which takes into account the effect of the water vapor layer on wave propagation, exhibited notable disparities. This suggests that, under certain conditions, this effect may not be as relevant as initially thought in our test environment. Data resolution and sampling frequency may have contributed to these discrepancies and could be subjects for future research improvements.

6. Conclusions

In this text, different deployments of radio signal transmission and reception have been documented, both in relevant environments (near the coast) and in real-world settings (farther from the coast), characterizing various communication scenarios and technologies.

In the marine environment, diverse technologies have been deployed for a range of applications, including long-distance communication and sensor data transmission. This deliverable has documented tests conducted at the laboratory level and deployments in a long-distance marine environment, from various locations, focusing on the previously selected technologies. Each of them exhibited varying ranges, but all achieved successful communications. GSM stood out with the greatest range, reaching 20 km, followed by Wimax at 14 km, and finally, LoRa at 6 km. The choice of which technology to deploy in the marine environment will depend on the specific use case and communication requirements of each project. It is essential to select the appropriate technology, considering factors such as range, speed, reliability, and cost.

Regarding the validation of electromagnetic wave propagation loss models developed in the first work package of the project for marine environments, campaigns were conducted to collect experimental data in marine settings, which could then be compared with the expected results from these models. The comparative analysis indicates that the most robust model appears to be the two-ray model. On the one hand, the free-space loss model partially underestimates the measured losses, and on the other hand, the three-ray model, due to its sensitivity to the height of the evaporation duct, is more complex to accurately adjust. Furthermore, as an improvement for future tests, it is suggested to increase the data sampling resolution in signal reception to capture fine details of spatial loss dependencies.

The use of technologies like WiMAX, LoRa, and others identified in this study can enhance communication in these activities and, ultimately, contribute to a more sustainable exploitation of marine resources. The ability to collect real-time, accurate data and transmit them efficiently is essential for informed decision making and the preservation of marine biodiversity.

Author Contributions: Conceptualization, I.F.; methodology, I.F. and H.E.; validation, H.E. and R.M.; formal analysis, I.F. and E.M.; data curation, R.M.; writing—original draft preparation, H.E. and I.F.; writing—review and editing, I.F. and R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Instituto de Fomento de la Región de Murcia (INFO) under the Program of grants aimed at Technological Centers of the Region of Murcia for the realization of non-economic R&D activities. Modality 1: Independent R&D Projects, with File No.: 2022.08.CT01.000041, and titled "MODEM. Investigación de múltiples tecnologías de comunicación para la mejora de redes de sensores inalámbricos en la monitorización del medio marino".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available on request due to restrictions (e.g., privacy, legal or ethical reasons).

Conflicts of Interest: The authors declare no conflicts of interest.

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