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Design and Deployment of a Wireless Sensor Network for the Mar Menor Coastal Observation System

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***Abstract*—The Coastal Ocean Observation System of Murcia Region (OOCMUR) was established in 2008 as a major scientific and technological infrastructure in Spain with the main objective of studying the impact of global climate change in the Mediterranean. The coastal lagoon of Mar Menor in southeast Spain was chosen as the first region to be monitored because it is one of the most hypersaline coastal lagoons in the Mediterranean, with a limited exchange of water with the open sea, and it is the largest in Europe. Wireless sensor networks (WSNs) offer an efficient and innovative solution for oceanographic monitoring, allowing a higher density sensor deployment, at a lower cost. This paper presents the design of an *ad hoc* WSN system and a control software for Mar Menor monitoring using a buoy structure with sensors, energy harvesting, and communications platform. The study focuses on the oceanographic interest of the selected marine area, details of network deployment, the custom-designed sensor nodes, and the results of system operation.**

***Index Terms*—Buoy, coastal lagoon, oceanographic monitoring system, sensor, wireless sensor network (WSN).**

I. INTRODUCTION

COASTAL ecosystems, mainly coastal lagoons, which are among the most productive ecosystems of the planet and further play a major role in coastal fisheries as nursery and feeding grounds, are considered to be particularly vulnerable to human factors causing the erosion of marine biodiversity [1]. Furthermore, in coastal lagoons, fishing activity is highly dependent on migratory patterns of species, as most of the target species use the lagoon only during a part of their life cycle, going back to the open sea for reproduction. Nevertheless, our understanding of the ecological factors driving the spatial and temporal variability of species and habitats in the coastal zone [2] is strikingly poor. Such an understanding is needed for a correct implementation of any management and enhancement measures. These measures are important for the functioning of coastal ecosystems linked to hydrographical processes which explain the connectivity between populations.

Observing systems for coastal zones are increasing to better understand and manage these types of ecosystems. Oceanographic observation platforms measure physical, chemical, and biological variables of coastal water, and make real-time observation and supply information to help in decision-making purposes for mitigating and managing problems such as climate change, man-made impacts, variability of coasts, beach erosion, natural disasters, or the condition of ecosystems. These observation platforms are now becoming a reality in the countries most advanced in marine sciences (see Table I), and one of their characteristic features is technological innovation, particularly the development of new sensors and platforms for data harvesting in real time. The advances in the development of these systems pursue is progressive improvement in the information that is gathered (new variables and analysis of a larger range of space-time scales) and real-time data transmission.

Taking advantage of the opportunities offered by technological development in recent years, the Coastal Ocean Observation System of Murcia Region (OOCMUR) was established [3]–[5] as a special scientific and technological infrastructure promoted by the Spanish Ministry of Science and Innovation and the Regional Government of Murcia with the principal objective of addressing the aforementioned needs. OOCMUR was devoted to the study of oceanographic and ecological processes linked to alterations produced by climate change, especially in biodiversity and colonization of allochthonous species, focusing particularly on coastal lagoons, marine protected areas, and open coastal ecosystems.

Briefly, OOCMUR had three main goals: 1) technological developments for observation systems; 2) high-resolution hydrodynamic and ecosystem modeling; and 3) study of ecological processes under a global change scenario [6]. Technological developments for monitoring would include: underwater robots and vehicles, marine instrumentation, subsea communication and telematic services, new indicators and models for climate change observation and prediction, spatial and temporal scales for determining population connectivity, and wireless sensor networks (WSNs) applied to marine observation.

WSNs [7], [8] offer an efficient and innovative solution for oceanographic observation, allowing information gathering with greater space-time resolution by means of a higher density sensor deployment, at a lower cost. The idea is to have different sensor nodes forming a network that implements different physical and logical topologies for wireless information exchange and to have a single node to transmit that information to the base station by means of the requisite long-range connection in each case. This solution allows to deploy the measurement node when it is necessary.

Different sensors are used for instrumentation in these marine environments. However, this task is complicated by problems such as

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TABLE I
SOME EXAMPLES OF COASTAL OBSERVATION SYSTEMS

Country	Acronym	Observatory	Technology of real time data transmission
Canada	VENUS	Victoria Experimental Network Under the Sea	A network of about 50 km of fiber optic cables
France	OOV	Observatoire Océanologique de Villefranche sur mer	GSM
Germany	MARNET	Marine Environmental Monitoring Network in the North Sea and Baltic Sea	GSM
Greece	POSEIDON	POSEIDON system	Acoustic communication, Satellite INMARSAT-C, GPRS and Iridium
Spain	OOCMUR	Observatorio Oceanográfico Costero de la Región de Murcia	ZigBee and GPRS
Spain	OBSEA	Expandable Seafloor Observatory	Cabled observatory. Optic Ethernet network
Spain	SOCIB	Sistema de Observación Costero de las Illes Balears	Multi-plataform. HF radar, satellite, underwater and air communication.
UK	CCO	Channel Coastal Observatory	GPRS
USA	MARS	Monterey Accelerated Research System	Cabled observatory, 52 km undersea cable
USA	MVCO	Martha's Vineyard Coastal Observatory	Fiber-optic cable and high-speed wireless radio
USA	LOSOS-OOI	Laboratory for Ocean Sensors and Observing Systems (LOSOS) for Ocean Observing Initiative	Satellite and Line-on-Sight (Freewave, Wifi)
USA	RSN	Regional scale nodes (RSN) for OOI	Fiber-optic cable
USA	GCOOS	Gulf of Mexico Coastal Ocean Observing System	GSM/GPRS

retrieval of the data gathered and managed by these sensors, or the necessary measuring-point density.

WSNs have been used in recent years to monitor different natural areas such as lakes [9], rivers [10], ponds [11], and small marine areas [12]. Albaladejo *et al.* [13] report a detailed study of the most representative WSNs worldwide specifically for oceanographic monitoring. Various different technologies are in use with low transmission power and high sensor-node autonomy. WSNs, then, are an emerging technology with a promising future in the field of coastal oceanographic observation given the numerous advantages they offer over other solutions, particularly:

1) WSN nodes can be designed to have low power consumption and a relatively low cost;
2) different topologies can be used (tree, grid, etc.) with a multihop node-to-node routing protocol, so that data can be transmitted from a sensor node to a sink node several miles away;
3) large areas can be monitored by means of subnetworks with a suitable topology, each one linked to a node with a Global System for Mobile/General Packet Radio Service (GSM/GPRS) connection. In this way, moreover, operating costs are considerably reduced by the cost of the data transmission lines.

The aim of this paper is to describe the WSN-based coastal observation system deployed in the Mar Menor as a test base place. A part of the proposed system will be able to provide temporally reliable data series from a particular area in the Mar Menor in order to select and further test a high-resolution numerical model. These capabilities will provide useful information to biological processes such as the spread of organisms throughout the Mar Menor and recruitment patterns of larvae, and also to ascertain the reaction of this lagoon to climate change, by recording physical parameters such as variations of the sea level, derived temperature fluctuations, or the variation of other environmental parameters also related to human activity. This system might be used in any other coastal lagoon with minor technical adjustments.

Section II gives a detailed description of the study area, highlighting the interest of the monitoring zone and the technology used to implement the proposed deployment. Section III provides a description of material and methods used, in terms of sensors, electronics, mechanical, and software design. It describes as well the model of a complete deployment to monitor the Mar Menor coastal lagoon which will be carried out in different phases to validate the proposed system (the results of the first one are presented in this paper). The results and discussion about experimental data of first deployment are presented in Section IV. The conclusions and future plans are discussed in Section V.

II. DEPLOYMENT SITE

Oceanographic monitoring by means of coastal observation systems can embrace a wide variety of solutions, determined essentially by the scientific purpose and the scope of the monitoring, environmental, and marine conditions in the target area, and last by the budget available for the project. It is these three criteria: 1) purpose/scope; 2) location; and 3) budget that will determine the specific kind of infrastructure used and the deployment of one or another system.

The case envisaged in this work is a special example as regards monitoring, both in terms of the scientific purpose (outside the scope of this paper but can be found in articles such as [14]–[16]) and of the location of the coastal area chosen. Moreover, the buoy system used is designed to a low cost as is detailed in Section III-B.

A. The Interest of the Monitoring Area

The Mar Menor coastal lagoon (as Fig. 1 details, located on the southeast coast of Spain in latitude $= 37.726719$ and longitude $= -0.788070$) covers an area of 180 km^2, 8 mi from the Cape Palos marine protected area central part. This lagoon is connected with the Mediterranean Sea through three open inlets ("Las Encañizadas," "El Estacio," and "Marchamalo"). Inside the lagoon, there are five volcanic islands which influence the circulation patterns [17]. The main spatial dimensions of the lagoon are: north–south length 18.4 km, east–west length 8.9 km, water depth lower than 6.5 ms, salinity ranges between 42 and 47 gr/L, and pH level 7.12–8.45.

The first significant step in the monitoring process is to define the strategic points in the lagoon that are to be studied. The three inlets in La Manga del Mar Menor (see Fig. 1, right) are areas of strategic interest for determining the boundary conditions for the models, as they are the sole means of communication between the Mar Menor coastal lagoon and the Mediterranean Sea. The horizontal pressure gradient at both sides of the inlets produces a considerable exchange of waters through them thus being needed to accurately measure the sea level at either end of them. The speed and direction of the marine currents are also valuable parameters needed to be measured in the narrow part of each of these inlets because tides, winds, and atmospheric pressure affect the

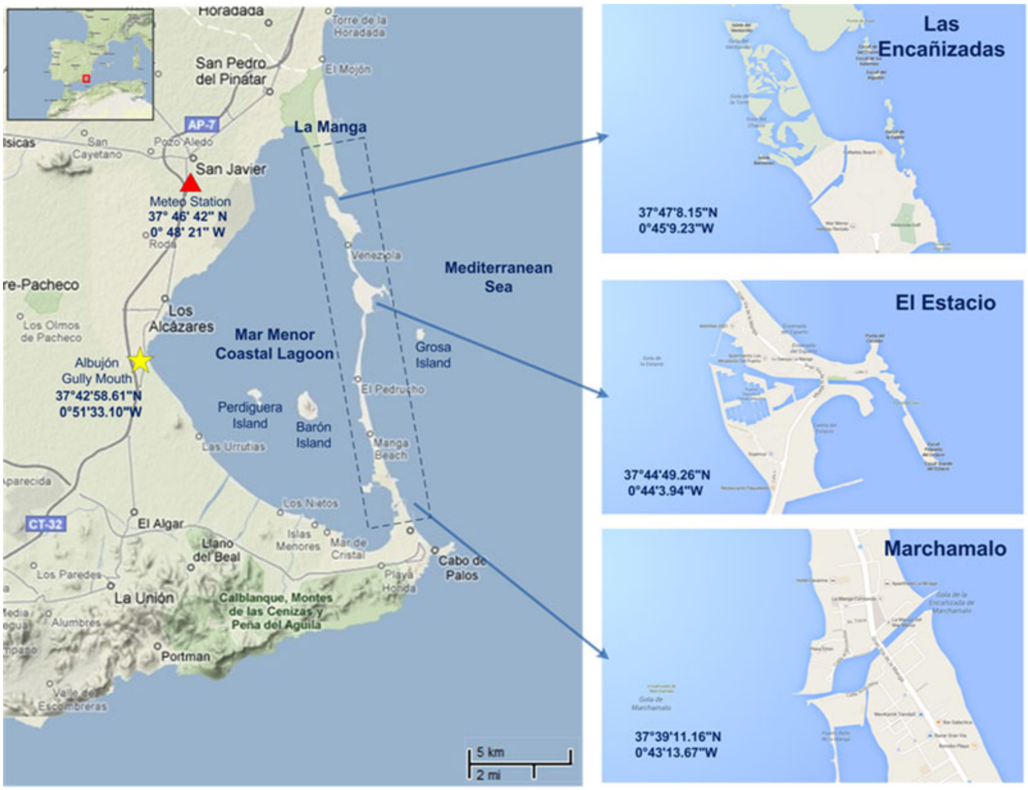


Fig. 1. Location of the Mar Menor coastal lagoon and inlets.

sea level. To produce a comprehensive survey of degrees of variation in the sea level of the waters adjacent to La Manga (Mediterranean Sea and Mar Menor lagoon), two additional points of interest were identified in the Mediterranean Sea: one close to Isla Grosa and another at Cape Palos.

In addition to the zones of interest mentioned above, the Albujón Gully Mouth is a key point to monitor because it is the only permanent fresh water flow into the lagoon that comes from the mouth of the Albujón watercourse. It is located at the western part of the lagoon (indicated with a star in Fig. 1), which is the main nitrogen entry to the lagoon coming from the intensive agriculture in Campo de Cartagena having a decisive impact on the eutrophication process in the lagoon. Last, the Spanish Meteorological Agency (AEMET) station at San Javier airport (15 km northwest from the deployment area, shown in Fig. 1) is used to supplement the meteorological information.

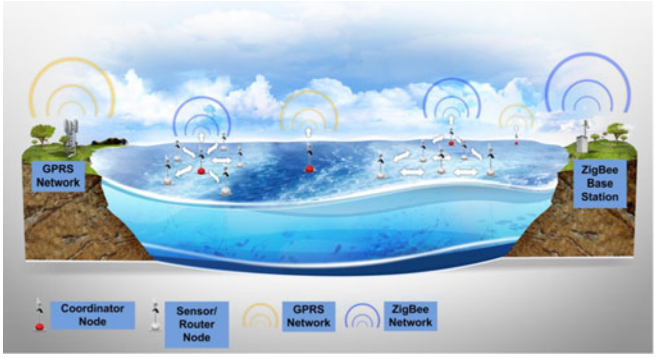


Fig. 2. Deployment of a WSN for oceanographic monitoring.

III. MATERIALS AND METHODS

A. Technology and Proposed Deployment

This paper presents a progress of the buoy and the analysis system presented on [18]. In the mentioned work several tests were performed, including first coverage tests, hardware tests, and mechanical structure tests of the buoy, being all of them satisfactory. Both works contribute to the state-of-the-art technology about applications of WSN [7]. We propose a WSN to monitor the physical environment of the Mar Menor and its interaction with the Mediterranean Sea. According to the specifications of a WSN [7], of all the wireless communications technologies available on the market (WiFi, bluetooth, WiMAX), ZigBee [19] is the best option as it provides key features that justify its choice. First, it is an open global standard that operates in the 2.4-GHz unlicensed band. Second, it is a secure and reliable technology that uses low-bandwidth data communications with low power, providing scalable networking solution that allows high density of measurements in a relatively small area. In addition, our devices use a Texas Instruments MSP430 microcontroller with high input/output (I/O) management capacity, low energy consumption, and high performance. This microcontroller is capable of easily interfacing a ZigBee radio-frequency (RF) transceiver and including the ZigBee stack in its code, so this was one of the main reasons for choosing this WSN technology.

The coverage of a ZigBee WSN depends mainly on the quality of the antennas used with the devices. Since Zigbee technology is a low energy communication system, the power transmission must be low. The use of high-gain antennas and the choice of the right locations to install the nodes are key factors to guarantee a good coverage and a reliable communication among the devices. Furthermore, Zigbee offers different network topologies and diverse types of nodes that can be combined and arranged in order to deploy a network as dense and wide

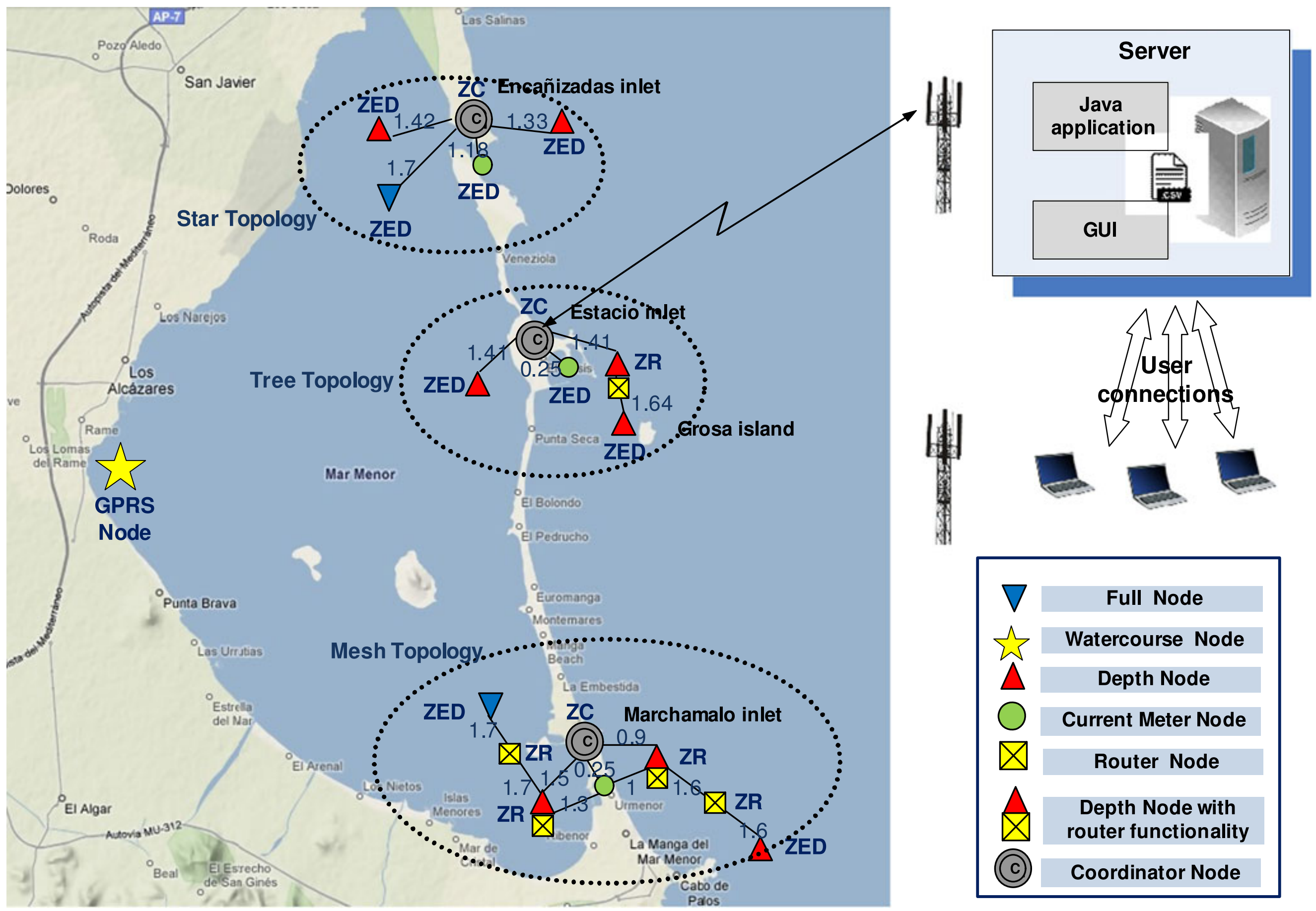


Fig. 3. Proposed deployment of WSNs in the Mar Menor.

as needed. As the number of nodes of a ZigBee network increases, communication jam may occur in some areas and, hence, compromise the robustness of the network. In such situations it is advisable to change the node locations or install a ZigBee router for a specific area (as explained below). In this way, multiple paths are provided for messages to reach a coordinator, increasing the coverage of the end devices in the network. In some cases, it is not possible to use Zigbee due to limited range of signal coverage; in these situations, isolated locations are monitored using GPRS nodes. Fig. 2 shows an example of the use of Zigbee communications with different topologies and an example of GPRS nodes in buoys far from the coastal line.

The ZigBee standard defines three types of devices depending on their role in the network [20]: ZigBee coordinator (ZC), ZigBee router (ZR), and ZigBee end device (ZED). There are three basic topological types in ZigBee: star, tree, and mesh network. In the three topologies, there is a single node that performs the role of ZC, responsible for centralizing acquisition and communication pathways among the other ZED and ZR devices. In the star topology, the coordinator is at the center; in the tree topology, the coordinator is the tree's root; and in the mesh topology, at least one of the nodes has more than two connections.

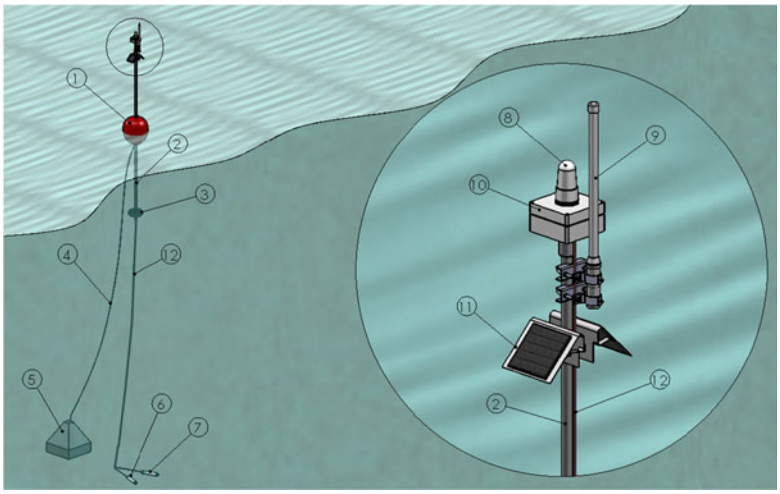
Tests will be run on each of the WSN topologies that ZigBee supports, taking into account the areas it is proposed to monitor (Fig. 1). The WSN proposed here will be composed of different types of nodes placed at strategic locations defined in the previous section (Fig. 3).

In total, 14 monitoring points are proposed as of interest for capturing the relevant parameters to obtain hydrodynamic models (Fig. 3). Following is a detailed description of the deployment setup to address these needs.

TABLE II
SENSOR NODES FOR COMPREHENSIVE MONITORING OF THE MAR MENOR

Sensor Node	Measurement	
Depth	• Water pressure	
Current meter	• Current velocity	
Watercourse	• Temperature • Water pressure • Salinity	• Turbidity • Dissolved oxygen • Chlorophyll • Nitrate
Full	• Water pressure • Current velocity • Salinity in one point • Profile of temperature	

The network considers four types of sensor nodes (see Table II): the depth node, the current meter node, the watercourse node, and the full node. The watercourse node is a GPRS node and the others are ZEDs in the WSN. Depth nodes take samples of sea level (using pressure sensors) and temperature, with sensors located at the bottom of the sea. Current meter nodes measure current speed and direction. Full nodes monitor sea level, currents, salinity, and temperatures profiles by temperature and salinity probes along the buoy's line. The watercourse node measures not only the basic physical parameters (temperature, pressure, and salinity), but also other parameters such as turbidity, dissolved oxygen, chlorophyll, and nitrates. This last node completes the hydrodynamic study made by the WSN in the three inlets.



Protocol	ZigBee/GRPS
Antenna	Omnidirectional 8 dB/ANT-GNR600
Range	3 km (line-of-sight)/ Mobile network
Harvesting system	Rechargeable PoLi (3.7 V, 5 A·h) 2x2.5 W solar panels
Electronic housing	12x12x7 cm IP68 box
Signalling	Beacon light & flag
Float system	50 x 40 cm polyvinyl chloride float
Counterweight	7 kg
Anchor system	Mooring line & anchor
Dimensions	3 m (longitude) x 0.4 m (diameter)
Weight of buoy	12 kg (in air)

Fig. 4. Marine buoy and buoy characteristics, including the adopted protocol, antenna, and range depending on the type of node (ZigBee/GPRS) designed and manufactured by the Electronic Systems and Engineering Division (DSIE) of the Universidad Politécnica de Cartagena, Spain.

The ZCs will transmit the information received from the sensor nodes or routers and relay it to the data server located around 30 km away at the Universidad Politécnica de Cartagena, via GPRS. This server includes a Java application to collect data from the nodes, to process and to store data in a CSV file, and another application (GUI in Fig. 3) has been developed to show data to the users.

The nodes, which have data acquisition capacity, will be placed in the target area as shown in Fig. 3; they will be distributed in three different subnetworks, each having a ZC node, and with a different topological configuration. At the Encañizadas inlet, a star network will be deployed since the distance between the ZEDs and the ZC is small enough to allow a direct connection. The network to be deployed at the Estacio inlet will have a tree topology since the distance from one of the ZEDs to the ZC exceeds the range of coverage, so that a ZR node will be required. Last, the network at the Marchamalo inlet will have a mesh topology to allow for alternative message routings in the event of a node failure.

It is proposed to deploy sensor nodes to monitor the lagoon acting as routers (depth node with router functionality in Fig. 3), and others to act as routers only (router node in Fig. 3) so as to cover the entire monitoring area. For its part, the watercourse node will communicate via a GPRS link independent of the ZigBee subnetworks, owing to the distance separating them (7 km to the nearest node).

B. Description of the WSN Buoys

The sensor nodes that monitor the parameters described in the previous section have to be mounted on a suitable mechanical structure and must meet a number of particular requirements dictated by conditions in the marine environment (see [9] for a detailed description). In addition, power consumption requirements and communication needs were taken into consideration in the design of the node, as described below.

Maintenance requirements and the associated cost will be reduced even further if the node battery life of the nodes can be prolonged, as less intervention will be needed. WSN node autonomy can be enhanced by equipping them with energy collection systems so that their batteries can be recharged using solar or wind renewable energies thus solving the problem of complexity and high cost of infrastructures based on wired systems. Besides, the design must be such that the network can be deployed, maintained, and recovered at minimal cost. The component elements of the systems to be deployed must be as light as possible to facilitate their installation. A buoy-based node was selected as the best choice to fulfil these requirements. The node's flotation system (buoy) must be robust and composed of nonpollutant materials that can withstand environmental marine conditions. In this way, we can guarantee the durability of the structure and minimize maintenance requirements.

From a mechanical point of view, all the buoys shown in Fig. 3 are identical, although there are differences of functionality that only affect the electronic systems that each one contains.

Fig. 4 shows the sensor buoy designed. It meets all the requirements cited in the introduction to Section III, with the main features noted there.

The principal properties are as follows.

1) The buoy is very light (12 kg) and can thus be transported, deployed, and recovered by a single person.
2) The battery and the solar panels provide unlimited autonomy. Without sunlight the buoy could function for approximately 15 days, according to the consumption studies conducted (see [21]).
3) The radio module used for the ZigBee nodes (Texas Instruments CC2520-CC2591EM) configured with an output power ratio of 17 dBm, in conjunction with a omnidirectional antenna of 8 dB placed 1.5 m above sea level, guarantees reliable communication with another zigbee node located in direct line of sight. The GE863-GPS communications module has been used for the GPRS buoy, with a GSM antenna of 27-dBi power gain.
4) The cost of the buoy is relatively low (around 500 euros).

Capacity for simultaneous environmental sensors with several electrical interfaces (4–20 mA, 0–2.5 V, SDI-12, and RS232).

C. Electronic Design

The electronic used in this buoy system was described in [21]. It is a design performed at the Universidad Politécnica de Cartagena and later improved by the Widhoc Smart Solutions S.L. This is a modular design composed of two electronic boards based on MSP430F2618 microcontroller and it allows to connect sensors with RS-232 and

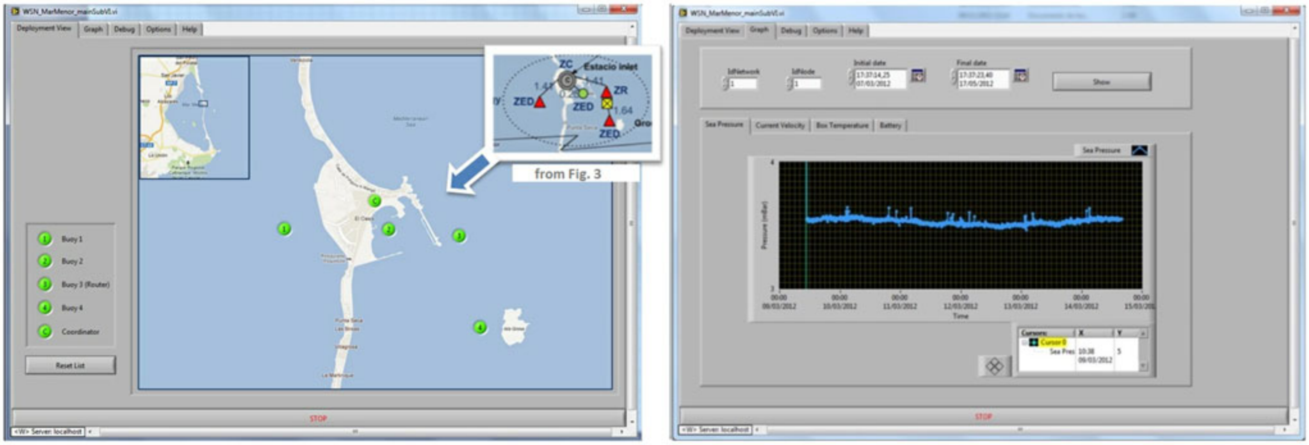


Fig. 5. User application. (a) Deployment view. (b) Graphical representation.

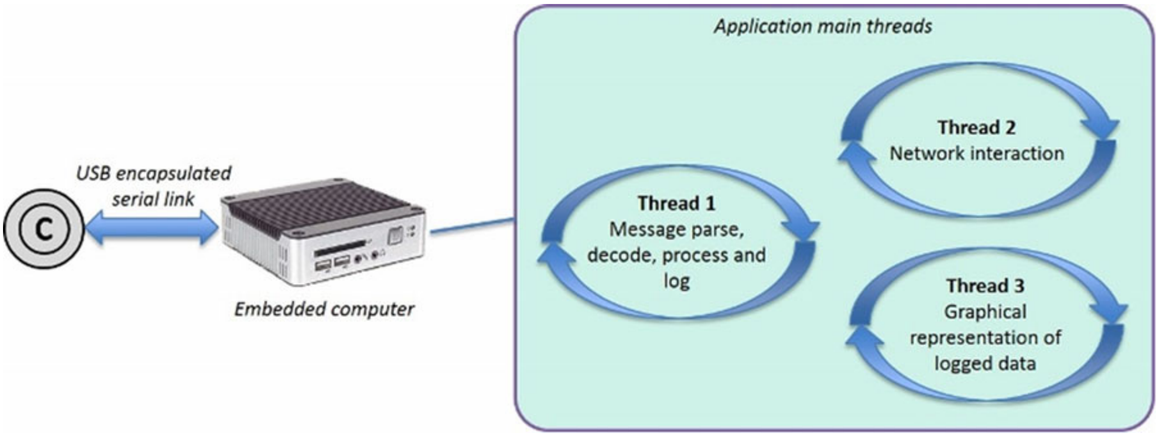


Fig. 6. Application main threads.

4–20-mA interfaces. Moreover, it includes a real-time clock with which to generate timer interrupts and show real time at which the sample was taken. This electronic design also includes solar panels and recharge battery to manage the power energy and so to increase the autonomy of the buoy (see more details in [21]).

D. Software Design

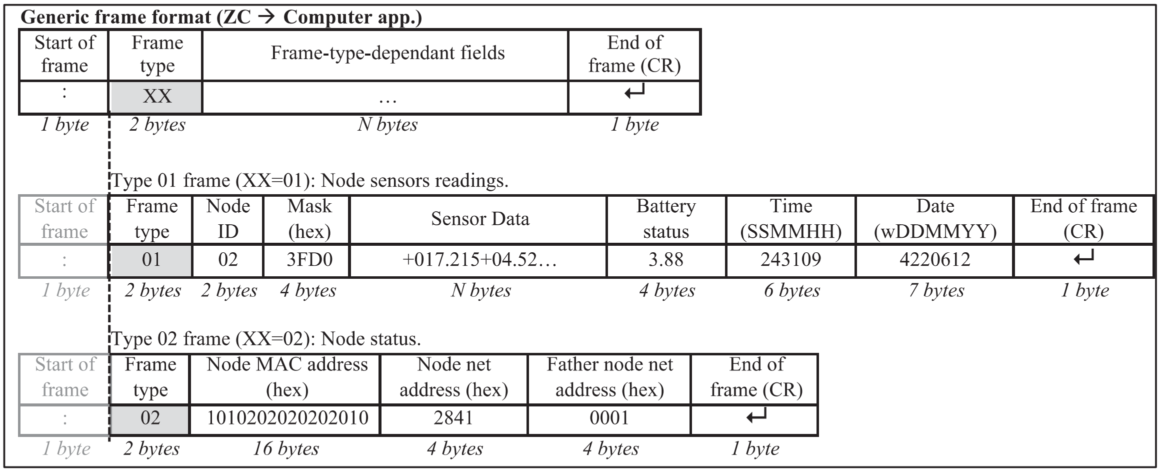
A LabVIEW user application was implemented for the harvesting, processing, and storage of information from the sensor network. LabVIEW is an open development platform from National Instruments that has gained acceptance in many different application areas and industries in the last years. Its core, the LabVIEW graphical programming language, enables scientists and engineers to develop complex measurement and control applications very quickly and easily [22].

Each ZC is connected to an embedded computer using a USB interface that encapsulates a virtual asynchronous serial communication. The computer runs the application that provides the graphical user interface, collects and logs data from the sensor network, and sends different commands to set up the nodes or modify their behavior. The front panel (user interface) of this application is shown in Fig. 5(a) and (b).

The application can be accessed remotely with any device that offers internet connection end gives the user a clear and orderly view of the data and of the interaction with the network nodes. After processing, the information is stored in a data base for various analyses, both real time and asynchronous. The main view of the user application shows the geographical location of each node and its network connection status (green if connected and red if not).

The format of the frames between ZED and ZC is established by the ZigBee standard, while the ZC is responsible for both transferring all the data collected by the network nodes to the computer and sending certain commands to them. So a specific format was defined for these data frames using binary-to-text encoding to ease the decoding of the frames by the computer application. Thus, these frames are composed of ASCII-printable characters. To perform these functions and manage all the data, the application is organized in various threads. The most important ones are shown in Fig. 6.

Thread 1 is responsible for parsing, decoding, processing, and logging the messages received from the ZC. This thread updates node states in the user interface, records data from sensors (including the node ID) in a CSV file, and updates the address table. This table includes relevant information of the current nodes in the network: node ID is the media access control (MAC) address, the network address, and the father node address. Fig. 7 illustrates the different fields that compose the frames sent by the ZC to the computer. These frames are categorized in two types: 1) type 01 for node sensor readings (including sensor data, battery status, and time and date stamp); and 2) type 02 that corresponds to the status information of nodes updated in the aforementioned address table.



Generic frame format (ZC → Computer app.)

Start of frame	Frame type	Frame-type-dependant fields	End of frame (CR)
:	XX	…	↵
1 byte	*2 bytes*	*N bytes*	*1 byte*

Type 01 frame (XX=01): Node sensors readings.

Start of frame	Frame type	Node ID	Mask (hex)	Sensor Data	Battery status	Time (SSMMHH)	Date (wDDMMYY)	End of frame (CR)
:	01	02	3FD0	+017.215+04.52…	3.88	243109	4220612	↵
1 byte	*2 bytes*	*2 bytes*	*4 bytes*	*N bytes*	*4 bytes*	*6 bytes*	*7 bytes*	*1 byte*

Type 02 frame (XX=02): Node status.

Start of frame	Frame type	Node MAC address (hex)	Node net address (hex)	Father node net address (hex)	End of frame (CR)
:	02	1010202020202010	2841	0001	↵
1 byte	*2 bytes*	*16 bytes*	*4 bytes*	*4 bytes*	*1 byte*

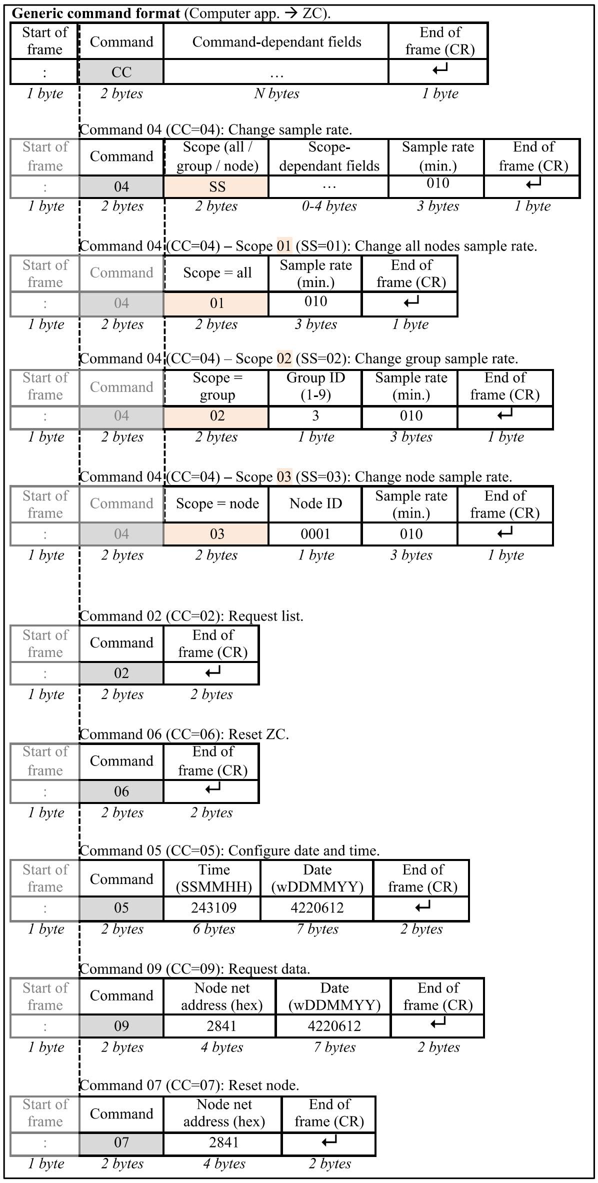
Fig. 7. Format of the frames sent by the ZC to the computer application.

Thread 2 manages the interaction of the application with the network nodes. Thus, the user can do things such as changing buoy sampling frequencies, configuring buoy date and time, remote resetting of buoys and retrieval of data in the event of loss of contact between the buoy and the base station. The allowed actions are described as follows:

1) change sample rate of the network, a group, or a specific node;
2) request list of nodes; upon reception of this command, nodes will send their status to the ZC;
3) reset coordinator;
4) request data from node; after reception of this command, the node sends the data for a specific day stored in its iternal SD card;
5) configure date and time of the network nodes;
6) reset end device; resets a specific node.

To perform these actions, a generic command frame was establish as shown in Fig. 8. The command field determines the specific format for each of the command-specific frames. These frames are received by the ZC which sends the appropriate messages to the node network.

Thread 3 manages the graphical representation of the data from the selected node. Fig. 5(b) shows an example of the graphical representations of pressure data gathered over ten days.



Generic command format (Computer app. → ZC).

Start of frame	Command	Command-dependant fields	End of frame (CR)
:	CC	…	↵
1 byte	*2 bytes*	*N bytes*	*1 byte*

Command 04 (CC=04): Change sample rate.

Start of frame	Command	Scope (all / group / node)	Scope-dependant fields	Sample rate (min.)	End of frame (CR)
:	04	SS	…	010	↵
1 byte	*2 bytes*	*2 bytes*	*0-4 bytes*	*3 bytes*	*1 byte*

Command 04 (CC=04) – Scope 01 (SS=01): Change all nodes sample rate.

Start of frame	Command	Scope = all	Sample rate (min.)	End of frame (CR)
:	04	01	010	↵
1 byte	*2 bytes*	*2 bytes*	*3 bytes*	*1 byte*

Command 04 (CC=04) – Scope 02 (SS=02): Change group sample rate.

Start of frame	Command	Scope = group	Group ID (1-9)	Sample rate (min.)	End of frame (CR)
:	04	02	3	010	↵
1 byte	*2 bytes*	*2 bytes*	*1 byte*	*3 bytes*	*1 byte*

Command 04 (CC=04) – Scope 03 (SS=03): Change node sample rate.

Start of frame	Command	Scope = node	Node ID	Sample rate (min.)	End of frame (CR)
:	04	03	0001	010	↵
1 byte	*2 bytes*	*2 bytes*	*1 byte*	*3 bytes*	*1 byte*

Command 02 (CC=02): Request list.

Start of frame	Command	End of frame (CR)
:	02	↵
1 byte	*2 bytes*	*2 bytes*

Command 06 (CC=06): Reset ZC.

Start of frame	Command	End of frame (CR)
:	06	↵
1 byte	*2 bytes*	*2 bytes*

Command 05 (CC=05): Configure date and time.

Start of frame	Command	Time (SSMMHH)	Date (wDDMMYY)	End of frame (CR)
:	05	243109	4220612	↵
1 byte	*2 bytes*	*6 bytes*	*7 bytes*	*2 bytes*

Command 09 (CC=09): Request data.

Start of frame	Command	Node net address (hex)	Date (wDDMMYY)	End of frame (CR)
:	09	2841	4220612	↵
1 byte	*2 bytes*	*4 bytes*	*7 bytes*	*2 bytes*

Command 07 (CC=07): Reset node.

Start of frame	Command	Node net address (hex)	End of frame (CR)
:	07	2841	↵
1 byte	*2 bytes*	*4 bytes*	*2 bytes*

Fig. 8. Format of the frames used to send commands from the computer application to the ZC.

E. Deployments of the WSN on the Mar Menor Lagoon

In the future, depending on the tourist activity in the area, the following deployments will be carried out.

1) Deployment of a WSN at El Estacio inlet. Of the three inlets that link the Mar Menor and the Mediterranean Sea, El Estacio is the one where there is the greatest exchange of water, and hence it is there that monitoring is of most oceanographic value when commencing surveys on underwater currents in the Mar Menor lagoon. There is a marina in the El Estacio inlet with surveillance facilities and a control tower. This means that the WSN can be more safely deployed and offers the means of checking whether the signaling measures adopted are adequate given the intensity of maritime traffic in the area.
2) Deployment of a WSN with a star topology at the Las Encañizadas inlet, which is the least frequented area.
3) A WSN with the a mesh topology will be deployed at the Marchamalo inlet, and the deployment will be completed after with the installation of the GPRS node.

Following the favorable results in the trial phases described in [21], in which mechanical, autonomy, and communications tests were

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Fig. 9. Real tests.

TABLE III
BUOYS LOCATIONS AND DEPTH OF PRESSURE SENSORS

	Pressure sensor depth (m)	*Location*
Buoy 1	0.65	37°39'44.22"N 0°44'3.78"W
Buoy 2	1.84	37°39'42.06"N 0°44'2.25"W
Buoy 3	1.68	37°39'41.12"N 0°43'57.20"W
Buoy 4	0.54	37°39'40.87"N 0°43'52.09"W

successful, the next was the operational deployment composed of four buoys in the Mar Menor to record data of the sea level (LMK807 sensor; see the Appendix) and environmental temperature (ECT air temperature sensor; see the Appendix). These trials are detailed in the next section, and since the first of the proposed star topologies was tested in the deployment/recovery trials in the Mar Menor reported in [21], it was decided in this phase to implement the tree topology, which entails the use of at least one ZR node and is also the least complex.

The previously mentioned trials were deployed between March 7 and June 14, 2012, around the "Dos Mares" yacht club in the southeast inner part of the Mar Menor coastal lagoon where a pier between the coast and the "El Ciervo" island was recently removed. Fig. 9 shows the buoys in real conditions and Table III details their location.

The location and bottom depth of the deployed buoys are showed in Table III. Temperature and pressure sensors were configured with a sample rate of 10 min. Bad data and outlines have been removed from the time series, smoothed and hourly decimated. To be able to compare sea level differences between stations, the mean value was subtracted.

Wind and atmospheric pressure data were acquired every 10 min from the Spanish Meteorological Agency (AEMET) station placed in San Javier (15 km from the deployment area). The absence of topographic barriers between the buoys and the meteo station allowed to assume the same meteorological conditions in the study area. Data were decimated and smoothed hourly, showing a high variability in the wind, blowing mainly from northeast and southwest (Fig. 10).

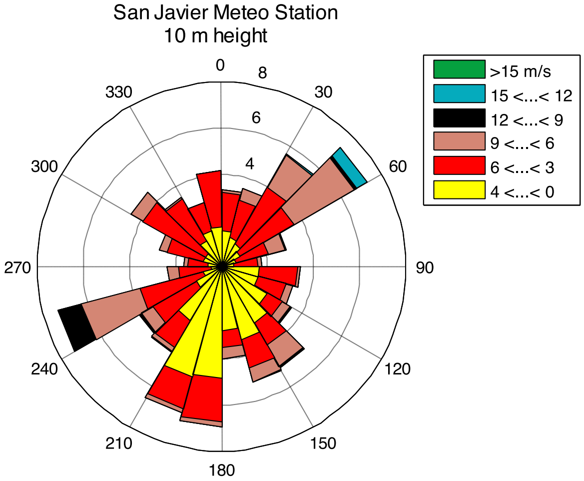

Fig. 10. The rise of the wind for the study period.

IV. EXPERIMENTAL RESULTS

This section describes data collected by the buoys in the trials described above. Data from air temperature and sea level for each buoy are presented.

Mean air temperature recorded for each buoy ranged between 14.58 °C (buoy 1) and 19.38 °C (buoy 3). Minimum temperature

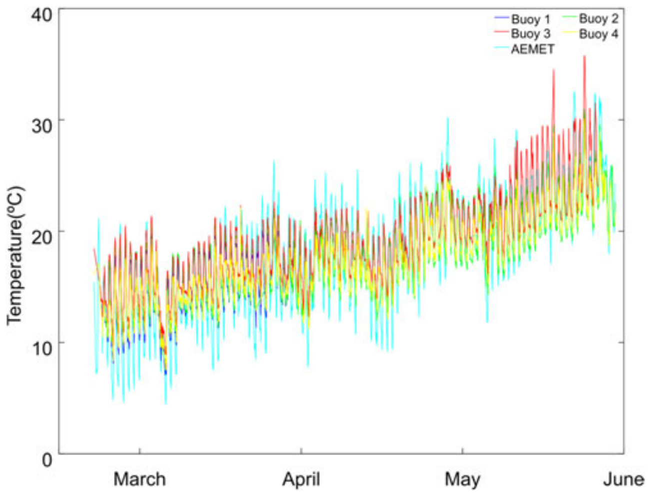

Fig. 11. Air temperature for each buoy.

TABLE IV
BASIC STATISTIC FOR THE SEA LEVEL AND AIR TEMPERATURE

	Date	Sea level (m) Min	Sea level (m) Max	Sea level (m) Std dev	Air temperature (°C) Min	Air temperature (°C) Max	Air temperature (°C) Mean	Air temperature (°C) Std dev
Buoy 1	09/03/12–14/04/12	−0.16	0.19	0.08	7.07	21.47	14.58	2.93
Buoy 2	09/03/12–14/06/12	−0.20	0.15	0.05	8.23	30.89	18.91	3.75
Buoy 3	07/03/12–11/06/12	−0.19	0.16	0.06	8.89	35.75	19.38	4.25
Buoy 4	07/03/12–14/06/12	−0.14	0.08	0.04	7.49	30.13	17.61	3.75

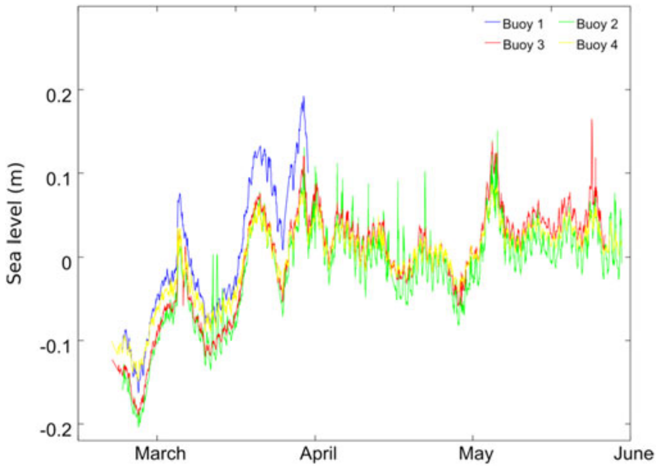

Fig. 12. Hourly sea level recorded by each buoy (note that buoy 1 was recording only from March to April, Table IV).

(7.07 °C) was recorded by buoy 1, whereas maximum temperature (35.75 °C) was recorded by buoy 3. During the three-month deployment, the mean temperature was increasing for all buoys starting at 15 °C by March and ending at 27 °C by the end of May. The measured air temperature showed a high correlation ($r^2 = 0.98$) with the AEMET station showing the capability of the buoys to measure reliable atmospheric data (Fig. 11).

The sea levels recorded by pressure sensors ranged from − 0.14 (buoy 4) to 0.19 m (buoy 1) (see Table IV). An increase in sea level was recorded by the four buoys from March to April showing a peak in mid March with an increase in the sea level of 0.3 m in 15 days. Although slight, this trend was also recorded by the other buoys (Fig. 12).

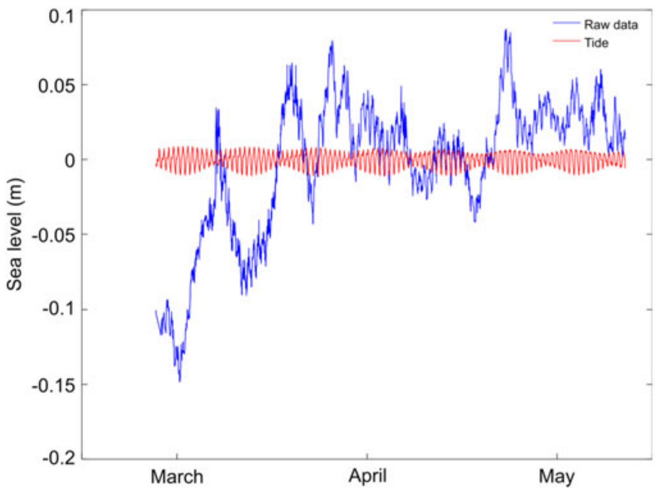

Fig. 13. Sea level tide analysis for buoy 4.

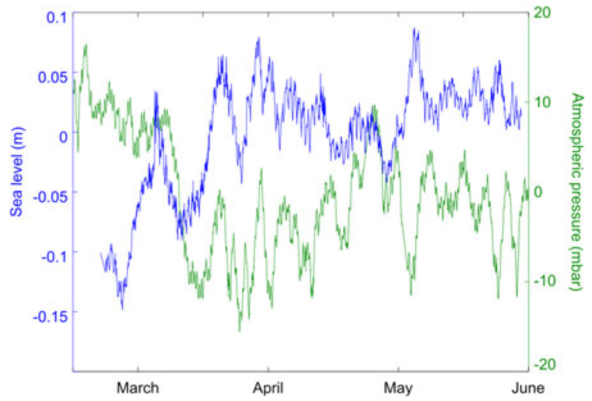

Fig. 14. Atmospheric pressure variations (mbar) and buoy 4 sea level variations (meter).

The location of the buoys defines sea level oscillations' behavior for each site. Buoy 4 showed lower sea water level oscillations due to restriction of water movements. On the contrary, buoy 1, deployed closer to the Mar Menor basin, showed a higher mean sea level (0.19 m). The high variability of data recorded by buoy 2 can be explained by its deployment site close to a sandbar of the El Ciervo island (Fig. 9) where northerly currents entering the restricted area from the Mar Menor basin collide with the coast, thus changing the sea level. Lower variations of buoy 3 are explained by the shallowness of the removed road from the island to the main coastline.

The recorded data are shown with additional analysis to understand the hydrodynamics of the lagoon. As an example, we show the tide analysis performed with the time series recorded by buoy 4 (Fig. 13). has been done to the longest serial data (buoy 4) [23]. The analysis shows that the tides in the area are very low, explaining only 1% of the total variance in the area. These results are in accordance with previous sea level studies carried out in the Mar Menor [24].

The inversed barometer effect [25] is a well-know phenomenon establishing an inverse relation between changes in the atmospheric pressure and the sea level variations. Fig. 14 shows data recorded by buoy 4 with the variations of the atmospheric pressure. We can see the inversed barometer effect along the time series, being showed clearly on April 1 with an increase of the sea level of 20 cm related with a decrease in the atmospheric pressure of about 20 mbar. In March this correlation is not so much clear due to strong winds (12 m/s) recorded during this period affecting the sea level and masking the inversed barometer effect during this period. The remainder of the series is a good example of the effects of atmospheric pressure on the sea level variations [26], [27].

V. CONCLUSION

This paper summarizes the deployment of a WSN for real-time monitoring of the Mar Menor lagoon. The design contemplates sensor nodes placed at oceanographically strategic locations and with the capacity of recording measurements of certain water parameters such as temperature, pressure, salinity, suspended nutrients, current velocity, etc. The first step to achieve the proposed design is the deployment presented in this paper. The first test consists of a WSN composed of four buoys with air temperature and pressure sensors. The information gathered by these sensor nodes is transmitted to a base station in the city of Cartagena (around 30 km away from the lagoon), where it is stored and analyzed following the technical models developed by our scientists. The system is scalable, so that additional sensor nodes can be incorporated in later phases. A software application has been developed *ad hoc* for this project. It offers multiple options to the user to interact with the system and to analyze the data. The data collected by the sensors installed on the buoys show the same behavior of the AEMET data with a correlation coefficient of 0.99 for temperature and a lag of 1 h. The coherence and phase analysis performed for the sea level measurements at La Isla del Ciervo and the atmospheric pressure at San Javier show a squared coherence of 0.85 above the 95% confidence level with a phase of 175° corresponding to the inversed barometer effect. These results confirm that the system is working correctly.

This infrastructure, the first of its kind in the context of the Mar Menor lagoon, will provide oceanographic researchers with valuable information to help them gain a detailed picture of the hydrodynamic behavior of the lagoon, as well as other parameters of interest. The fact that the network has been deployed in a marine environment for several months without any loss of data speaks for the solidity of the proposal and makes us confident that the deployment will be completed as planned.

APPENDIX

Sensor	ECT	ES2	LMK807
Measured data	Air temperature	Electrical conductivity (EC) and T	Pressure/Depth
Communication protocol	320 to 1000 mV @ 3 V excitation	SDI-12	4-20 mA
Range	−40 °C to 50 °C	EC: 0 to 120 dS/m T: −40 to 60 °C	0–10m 0–16m 0–25m
Resolution	0.1 °C	T: 0.1 °C EC: 0.001 dS/m	
Accuracy	5 to 40 °C: ± 0.5 °C −40 to −20 °C: ± 1.0 °C	T: ± 1 °C EC: ±0.01 dS/m	$\leq \pm 0.5\%$
External Power (VDC)	2.5 VDC @ 2 mA, to 3.6 VDC @ 7 mA	3.6–15 VDC	$V_S = 8 \ldots 32$ VDC
Consumption	2.5 VDC @ 2 mA, to 3.6 VDC @ 7 mA	0.03 mA quiescent, 0.5 mA during 300 ms measurement	<25 mA
Manufacturer	**Decagon Devices**	**Decagon Devices**	**SENSOTEC Instruments S.A.**
URL	http://www.decagon.com/	http://www.decagon.com/	http://www.sensotec-instruments.com/

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