Design and Implementation of a Wireless Sensor Network for Precision Horticulture

Juan A. López, Fulgencio Soto, Andrés Iborra, Pedro Sánchez, and Juan Suardíaz

Universidad Politécnica de Cartagena, DSIE,
Campus Muralla del Mar, s/n E-30202 Cartagena, Spain
{jantonio.lopez,pencho.soto,andres.iborra,
pedro.sanchez,juan.suardiaz}@upct.es

Abstract. A prototype wireless sensor network for measuring soil and environmental characteristics was developed and evaluated for purposes of scheduling irrigation on field vegetable farms. The system consists of a central base station connected to multiple sensor nodes installed in the field and distributed over several crops. The sensor nodes consist of specially designed hardware which transmits data to a base station inside the farm offices. The relatively low cost of the system (USD 6000 for a 20-sensor node system) allows for installation of a dense sensor population that can adequately represent inherent soil characteristics such us temperature, volumetric moisture content, salinity and so on. Additional sensors can be used to measure environmental variables and the quality of the water used to irrigate the crops. This paper describes our experience during the design and implementation of the wireless sensor network and its components in a field crop of Broccoli (Brassica oleracea L. var Marathon) in the semiarid region of *Campo de Cartagena* in Southern Spain. It presents the topology of the network, which was deployed using three types of sensor nodes (Soil-Mote, Environmental-Mote and Water-Mote).

Keywords: Wireless Sensor Networks, Motes, TinyOS, Precision Horticulture, Precision Agriculture.

1 Introduction

Precision agriculture (PA) and precision horticulture (PH) [1] are production systems which make it possible to more accurately predict crop development on the basis of site conditions. To that end it is important to gather as much information as possible on the soil, plants and environment. This is achieved with new technologies such as global positioning systems (GPS), geographic information systems (GIS), wireless communications and instrument systems.

In this context, Wireless Sensor Networks (WSN) [2] is a technology with a promising future. In fact a number of studies have been published in the last few years on applications of this kind using WSN in Precision Agriculture. For example, Camilli et al. [3] used a simulation to demonstrate the utility of a WSN in Precision Agriculture; Pierce et al. [4] described a platform that they had developed for local and regional networks and implementations of them in two Precision Agriculture applications in

N. Komninos (Ed.): SENSAPPEAL 2009, LNICST 29, pp. 27–42, 2010.

Washington State; and Morais et al. [5] described a prototype that they had developed for deployment on vineyards to monitor crops of this type.

This article describes how a WSN was set up on a horticultural holding. The farm is located in the *Campo de Cartagena* in the Region of Murcia, South-East Spain, in one of Europe's most important horticultural areas. In climatic terms, this is a semi-arid zone with annual rainfall of approximately 400 mm. But despite that, 190,000 ha, 31% of the cultivated area, is under irrigation.

The farm on which the experiment was conducted (Langmead España S.L.) practises ecological agriculture, also known as biological or organic farming. This is a way of growing crops and caring for the land that is respectful of nature and normally excludes the use of chemicals and genetically modified seeds. The principal aim of this kind of farming is to preserve the environment, maintain or enhance the fertility of the soil and produce foods with their own natural properties.

The holding on which the experiment was conducted is of average size for the region. It covers 1000 ha, with 250 crop fields scattered over the *Campo de Cartagena* and several kilometres apart (between 5 and 10 km approximately). The ultimate aim of this work was to provide the farm with an infrastructure consisting of a large number of sensors with which to ascertain crop water conditions in real time and make the appropriate decisions. For these reasons, and in view of the scattered nature of the crop-fields, wireless sensor networks are the ideal solution.

This article describes our experience in laying out a sensor network on a real farm holding; section 2 describes the experimental scenario where the sensor networks were deployed. Section 3 presents one of the system's main devices, the GAIA Soil-Mote, from the standpoint of hardware and software. In combination with the Hydra Probe II sensor, this mote is capable of recording the salient characteristics of the soil (temperature, humidity and salinity). This same section describes the power management and the autonomy of the sensor node, and also the characteristics of the associated Hydra Probe II sensor. This section closes with a brief presentation of the other sensor nodes that have been developed to implement the network (GAIA Environmental-Mote and GAIA-Water Mote), and the Data-Sink/Gateway. Section 4 then gives a brief description of the possibilities offered by the monitoring software as developed, which is run on a computer at the farm's central office. Section 5 reports the results achieved in a real installation, and finally section 6 summarizes the main conclusions and proposed future research.

2 General Characteristics of the Network Deployed

Figure 1 shows the characteristics of the experimental crop on which the system as developed was tested. This consisted of two fields lying about 8.7 and 5.2 km respectively from the farm offices. In each plot, ten GAIA Soil-Motes were deployed to monitor the condition of the soil, and an Environmental-Mote was installed to monitor the ambient temperature and humidity in the plots. A Water-Mote was also installed in one of the supply ponds to check the quality of the irrigation water by monitoring its electrical conductivity.

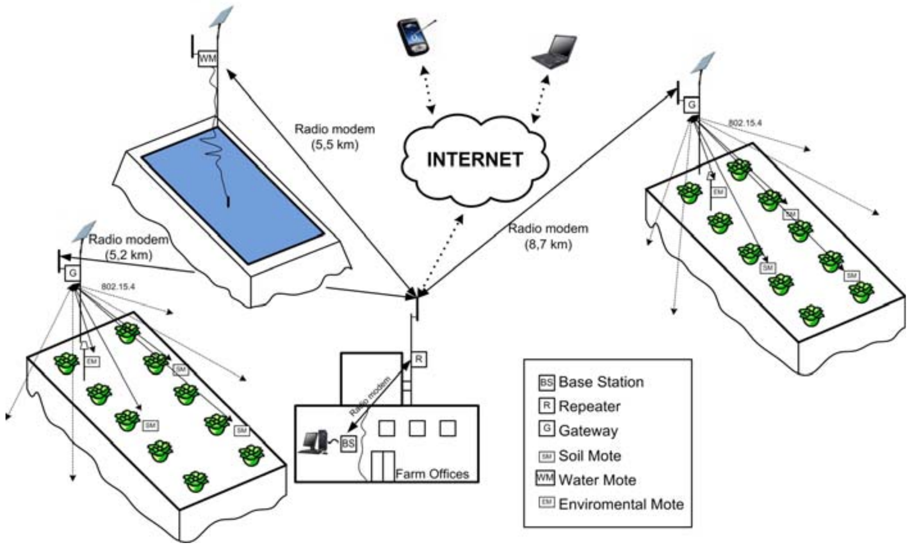


Fig. 1. Deployment of the wireless sensor network in two fields on a horticultural holding. The network also includes a sensor node to record the quality of the water supplied from a pond.

The device infrastructure required to interconnect the two sensor networks and the wireless sensor with the offices is as follows: (1) one Gateway for each of the sensor networks; (2) a Repeater located on the office building roof; and (3) a Base Station Mote inside the offices, physically connected to the monitoring computer. To assure wireless coverage of the system, Gateways were developed incorporating long-range radio modules in the design of the GAIA Soil-Mote. More information about hardware architecture of the overall system can be found in [6].

The nodes in each of these sensor networks were interconnected via IEEE 802.15.4 [7]. The reasons for the decision to use this standard will be explained in the part of the following section specifying the software architecture. When a message reaches the central computer through the Gateway, it is processed and its source and the information it contains are checked. On the basis of this information the message is stored in a relational data base, where a historical record is kept of the data gathered by the sensors and the times of the readings.

3 The GAIA Soil-Mote

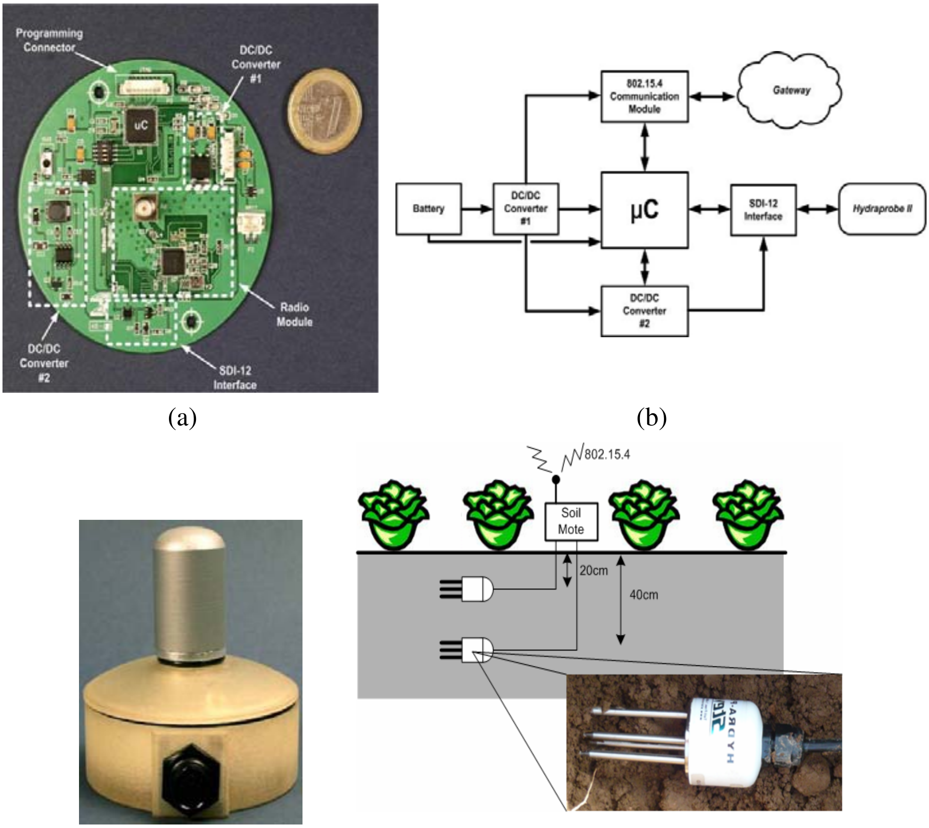
One important aspect of the motes is their capacity for connection with external instruments. There is a large group of sensors used in the field of Precision Agriculture which provide output by means of the SDI-12 protocol [8]. Commercial solutions based on this protocol include sensors marketed by Stevens, such as Hydra Probe II and EC 1200. Another major distributor, Campbell Scientific, markets sensors like CS245-L, CS408-L and WINDSONIC4-L. For that reason one of our objectives was to develop a mote capable of connecting to SDI-12-type external sensors. The chief requirements of this mote are as follows:

1. The mote must be a robust product in order to monitor soil parameters (temperature, humidity, salinity and conductivity).
2. The mote must have a SDI-12 interface so that any sensor with this protocol can be connected. However, it must be designed in such a way as to allow other SDI-12 sensors to be connected with minor variations in the software. In the present case, the mote must permit the running of two HP2 sensors to monitor the volumetric percentage. temperature, salinity and electrical conductivity of the soil at different depths.
3. The mechanical design of the device must be optimized for use on horticultural crops. This means that it must be suitable for installation at ground level and be small enough not to have to be removed when the crop is fumigated using farm machinery. The mote's casing must therefore provide IP67 standard protection and must be no more than 20 cm high (including the antenna). Also, to help avoid the motes being stolen, they should be painted a discreet colour. Note that although the design has to be optimized for horticultural crops, the motes must also be able to be used in other kinds of crops such as fruit crops, vineyards, etc.
4. To assure the greatest possible autonomy, the device must be able to communicate with a Sink-Mote or a Gateway via a highly reliable radio module compatible with standard IEEE 802.15.4. The motes are programmed with TinyOS [9], which uses the BMAC medium access algorithm, in order to optimize consumption. The working frequency is the 2.4GHz free band (ISM).
5. There is a limitation in that the gateway antenna must be at a height of not less than 5 m above the deployed nodes, and the maximum coverage between the sensor node and the gateway must be at least 100 m.
6. The Soil-Mote must be battery-operated with an autonomy of at least 10 weeks, which is the normal duration of a horticultural crop cycle.
7. On the software side, sensor readings are sent periodically to the sink node by way of the gateway. The reading frequency must be configurable from the sink-mote, over a range from 30 minutes to 10 days. The sink node must also receive hourly information on the battery status. In addition, for the deployment phase it was decided that the GAIA Soil-Mote should receive test messages from the sink node, which the latter would send back to the soil mote to assure proper communication between the two.

These were the basic requirements for the design of the GAIA Soil-Mote, which is described in the following sections.

3.1 Hardware Overview

Figure 2 shows two photographs of the GAIA Soil-Mote. The first one gives an idea of the size of the PCB, which was developed using SMD technology. As we can see, the mote card has been developed with a minimal number of components. This is due in part to the low power-consumption requirement and in part to the need to keep the mote size and manufacturing costs to a minimum. The following figures show the block diagram, the external appearance of the mote and its location in a horticultural crop. The sensor node is connected to two Stevens Hydra Probe II (HP2) sensors, which are described further below. The HP2 sensors are buried at different depths to monitor the main soil parameters. The core of the platform is a Msp430f1611 ultra-low power microcontroller from Texas Instruments. Wireless communication is provided by the Chipcon CC2420 radio module. The mote is powered with the help of a 3.7 V, 2000 mAh LiPo lithium polymer battery. Both the watertight casing and the sensor connectors have IP67 protection. Further information about the elements included in this device is presented in [9].



(a) (b)

(c) (d)

Fig. 2. Different views of the GAIA Soil-Mote. (a) PCB. (b) Block diagram. (c) External view of casing. (d) Image of device in field with detail of the sensor used.

When the battery is fully charged it delivers more than 4V. For that reason, as the block diagram shows, a low-consumption, low-dropout DC/DC converter (#1) is included to keep the battery voltage at 2.5 V. This voltage powers the microcontroller and the radio module. Then there is a second converter (#2) which transforms the 2.5 V to provide the 12 V output required by the HP2 external sensors. For efficient energy management, this converter is enabled only during the sensor reading process.

An “SDI-12 Interface” module has been included to enable the external sensors to be connected to the microcontroller’s UART. This interface is necessary for two reasons: the microcontroller and the external sensors work with different voltages, and moreover the two pins of the UART (Rx and Tx) have to be interconnected with the single two-way data line from the external sensors. All this is achieved by means of a tri-state buffer, a transistor and some discrete components so as to incorporate the SDI-12 interface in the mote. A single connector serves to connect up to 10 external sensors. Note that using only one external connector simplifies the PCB design of the board.

Finally, the block diagram shows the battery connected to the microcontroller by a voltage divider to allow periodic sampling of the battery level.

3.2 Software Organization

The device software was developed with TinyOS [10] version 2.0 as an operating system environment with the nesC [9] component-oriented programming language associated. TinyOS is an event-driven open-code operating system that provides the functionality needed for the proposed application, and it benefits from a large and active user community. We ported TinyOS to our platform and used a set of drivers that make the various I/O components available to the application programmer. Interested readers can find more information on this kind of programming in [11].

Figure 3 shows the nesC component diagram for the mote as developed. HP2C is a new component that is grafted on to TinyOS and is optimized for the use of two HP2 sensors. All the other components are operating system primitives which have been instantiated. Further details about the software architecture of the devices involved in the network can be found in [6].

The program entry point is supplied by the MainC component using the Boot interface. For the program to function, it is necessary to instantiate four TimerMilliC components, which are required to manage the program timer so as to know when to take a reading (Timer0), send the command to start up the reading process (Timer2) and start the data reading process (Timer3), and to be able to handle a time lag from when the process starts until the data are available (Timer1).

For communications, three AMSenderC components are required, one of the type CC2420ActiveMessageC and another of the type AMReceiver. The SendData instance of the AMSenderC component is used to send the data gathered from the sensors to the sink node or base station. The SendBattery instance sends the battery level data every hour. And finally, to facilitate the process of node deployment with the SendTest instance, a test message received from the Base Station is echoed. With the AMReceiver component it is possible to receive two types of messages: test messages and messages to alter the sensor reading timing. The last component, CC2420ActiveMessageC, is used to initiate the radio module and manage its operating time. In this way energy expenditure by the radio transceiver can be optimized. The nodes are specifically configured with a low-power-listening (LPL) period of 10 s. On this point it is important to remember that the frames sent and received with the selected TinyOS components are compatible with standard IEEE 802.15.4. We say that “the frames are compatible with the standard” because in order to optimize consumption TinyOS uses the BMAC medium access protocol instead of the MAC protocol, which is the one actually defined in the standard.

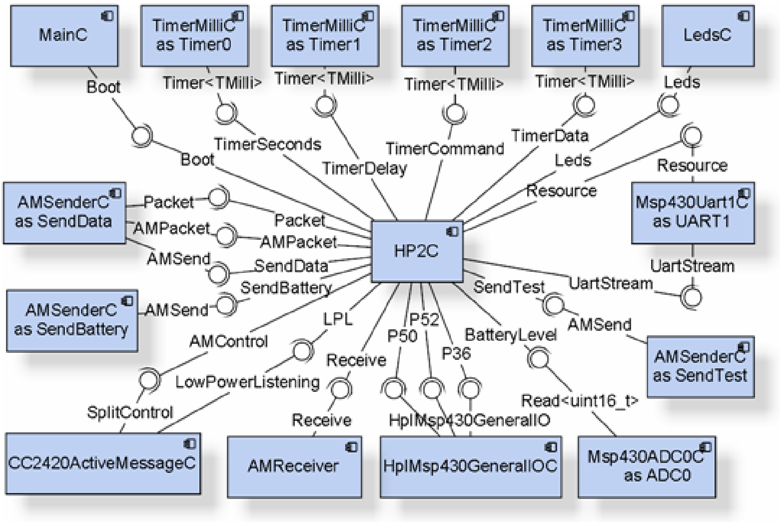


Fig. 3. GAIA Soil-Mote: nesC component diagram.

The Msp430Uart1C component is the one used to manage all communications with the HP2 sensor. With the LedsC component it is possible to access the 3 LEDs included in the mote, which are used to indicate states such as sending data from the mote, receiving a message and others. Msp430ADC0C allows sampling of the microcontroller ADC0 that is connected to the battery by way of a resistive voltage divider. And finally, a HPL (Hardware Presentation Layer)-level TinyOS component is needed to manage a series of microcontroller pins required for management of the SDI-12 interface (communications and DC/DC converter on/off).

3.3 Hydra Probe II Sensor

The Hydra Probe II sensor (HP2) (see figure 2.d) is a commercial product from Stevens Water Monitoring Systems, Inc. which is available with two different output interfaces: SDI-12 and RS485. Of these two versions, the most suitable for applications with low-consumption requirements is the SDI-12, since consumption in standby mode is 10 times less than with the RS485. Moreover, it only requires 3 wires (power, earth and data) as opposed to 4 required by the RS485 (power, earth, com+ and com-).

This sensor can provide various parameters for the ground, the most important being the temperature, volumetric percentage, conductivity and salinity of the soil. Calibration is carried out in the sensor itself, so that the data are received in digital-format physical units and ASCII code. Nevertheless, users may wish to perform their own calibration, and there is therefore the possibility of receiving uncalibrated data on the variables directly from the ADCs, in raw format.

As in any SDI-12 device, communication is achieved by sending ASCII commands and interpreting the response from previous ones. These commands can be used to take readings of the above-mentioned values and to configure parameters such as soil type, water constant, setting-up time and definition of the variables to be measured.

3.4 Power Management and Autonomy

In this section the objective is to estimate the autonomy of the device. As battery specifications are provided using AH terms, this can be determined with the battery parameters and the intensity required by the device.

The GAIA Soil-Mote has four functional states: standby for messages, communication module wake-up, sensor data acquisition and data transmission. Figure 4.a shows the mote's power consumption in each of these states. The worst-case scenario was taken for average consumption that is acquisition and transmission of data from the two sensors every thirty minutes. The ultimate aim of this study was to determine how much power the mote consumed on average, so as to relate the resulting figure directly to the capacity of the batteries and hence determine the device's autonomy. The mote's average power consumption may be determined thus:

$$\bar{I}_{\mathrm{soil-mote}} = \bar{I}_{\mathrm{s\,tan\,dby}} + \bar{I}_{\mathrm{receiv}} + \bar{I}_{\mathrm{acq}} + \bar{I}_{\mathrm{trans}} \tag{1}$$

where

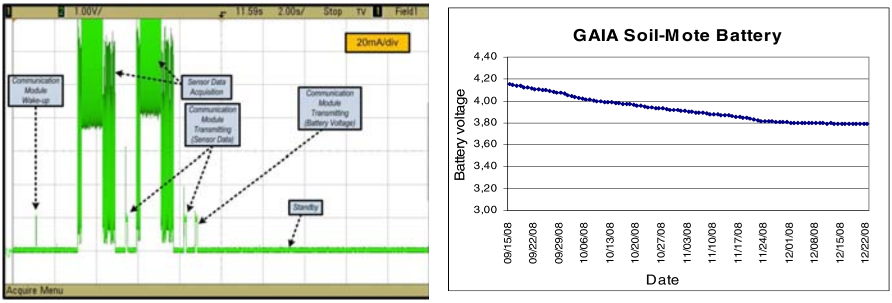
$$\bar{I}_{\mathrm{s\,tan\,dby}} = 0.25\mathrm{mA} \tag{2}$$

$$\bar{I}_{\mathrm{receiv}} \approx \frac{20\mathrm{mA} \cdot 15 \cdot 10^{-3}}{10} = 0.03\mathrm{mA} \tag{3}$$

$$\bar{I}_{\mathrm{acq}} \approx 2 \cdot \left(\frac{110\mathrm{mA} \cdot 1800 \cdot 10^{-3}}{1800} \right) = 0.22\mathrm{mA} \tag{4}$$

$$\bar{I}_{\mathrm{trans}} \approx 2.5 \cdot \left(\frac{25\mathrm{mA} \cdot 125 \cdot 10^{-3}}{1800} \right) = 0.00434\mathrm{mA} \tag{5}$$

Equation (2) represents the stand-by consumption and (3) expresses the average consumption in receiving mode for a 15 ms pulse every 10 s, with the radio switched on in the Low-Power-Listening period. Equation (4) presents a similar calculation, in this case multiplied by two, which is the number of sensors that are connected, and divided by 1800 s (30 minutes), which is the worst-case scenario for estimating autonomy. Equation (5) expresses the average consumption for the transmission of the sensor data and battery voltage. The equation is multiplied by 2.5 because the battery voltage messages are sent every hour. Equation (1) gives us an average current of 0.5034 mA, which, considering that the batteries are 2000 mAH, gives an estimated autonomy of 165 days. Note that the intensities of each state have been measured at the device input for a voltage of 3 V.



(a) (b)

Fig. 4. (a) Consumption states of the GAIA Soil-Mote: "standby"= 0.25 mA, "transceiver wake-up"= 20 mA, "acquisition"≈ 110 mA, "communication module transmitting (Sensor Data and Battery Voltage)"= 25 mA. (b) Evolution of battery rundown during laboratory tests.

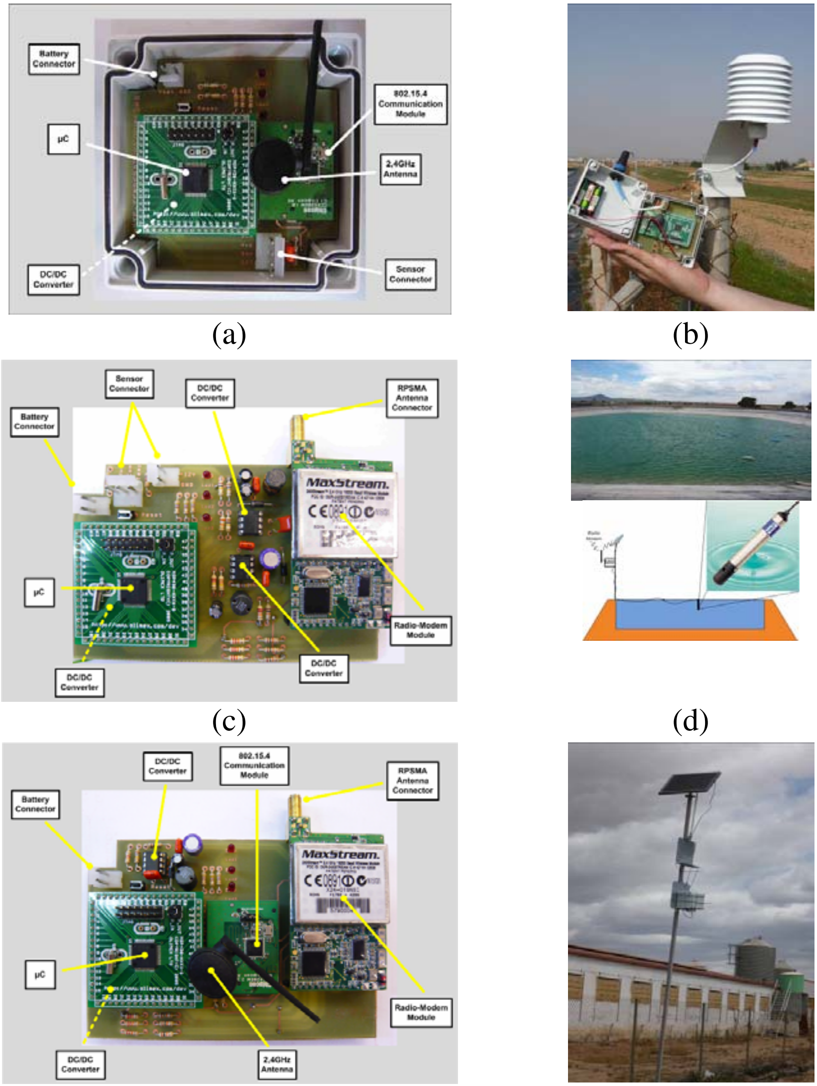
To check the above result, a real study was conducted in the laboratory (see figure 4.b) between September and December 2008, with the device taking sensor readings every 30 minutes. At the end of the study, the final value for the battery was approximately 3.8 V, well above the value of 2.7 V required at the main DC/DC converter input for the system to work properly.

3.5 Environmental-Mote, Water-Mote and Data-Sink/Gateway

The Environmental-Mote is a version of the GAIA Soil-Mote which has been equipped with suitable interface to enable it to connect the appropriate sensor. The Environmental Motes (see Figures 5.a and 5.b) record the ambient temperature and humidity parameters for a crop. The mote's architecture is similar to what we saw for the GAIA Soil-Mote except for the interface with the external sensors. Each mote is connected via the I2C interface to a Sensirion SHT71 sensor, which is placed inside a solar protection shield a metre and a half off the ground. These kinds of motes take readings of the cited parameters with a maximum parameterizable frequency of 2 readings/hour. The Environmental Motes must be located within a radius of roughly one hundred metres around the Data Sink/Gateway. In the experimental deployment, only one mote per field was used since the ambient conditions do not vary significantly from one field to the next.

The Water Mote (see Figures 5.c and 5.d) measures the temperature and salinity of the water supplied to the crop from an irrigation pond. In this case the mote is connected directly with the offices by way of a long-range radio module (XStream X24-019PKI-RA radio modem) with an 8dBi omni-directional antenna for outdoor use. The rest of the architecture is very similar to that of the motes described above. In this case a Stevens EC 250 sensor is submerged in the pond.

The two sensor outputs (temperature and salinity) are supplied in the form of a 4-20 mA signal; they are read by the microcontroller's ADC0 and ADC1 converters after the current loop is passed through a resistor. These parameters are read with a maximum parameterizable frequency of 2 readings/hour. The mote is powered by a solar panel and is enclosed in a watertight box placed on the edge of the pond. Its antenna is located on a mast at a height of approximately four metres.



(a) (b) (c) (d) (e) (f)

Fig. 5. Views of the different prototypes developed with similar architecture to the GAIA Soil-Mote. (a) Environmental-Mote. (b) Environmental-Mote installed in the field. (c) Water-Mote. (d) Water-Mote installed in the field. (e) Data-Sink/Gateway. (f) Data-Sink/Gateway installed in the field.

As we saw in Figure 1, the device infrastructure required to interconnect the two sensor networks plus the wireless sensor to the offices consists of: (1) one Data-Sink/Gateway for each sensor network; (2) one Repeater located on the office building roof; and (3) one Base-Station inside the offices, physically connected to the monitoring computer.

Figures 5.e and 5.f show a detailed image of the Data-Sink/Gateway along with its placement in the field. The microcontroller communicates with the crop motes via a short-range radio module and with the Repeater in the offices via a long-range radio module. The lifetime of the power supply is unlimited thanks to the use of rechargeable solar batteries.

In order to have a connection with the Base-Station in the offices, the main antenna has been placed on the office roof, at a height of nine metres. The main antenna and the Base-Station are also connected wirelessly. The Base Station gathers all the information generated by the sensor networks and transmits it to the monitoring application which was developed to handle that network. Similarly, it broadcasts any order from the software application over the sensor network. This device is composed of a long-range radio module (2.4 GHz) connected to a 3dBi omni-directional antenna, and a RS-232 interface for connection to the central computer. The Repeater is a commercial radio modem configured in repeater mode, which is connected to an 8dBi omni-directional antenna. This provides up to 16 km line-of-sight coverage in the open. No additional repeaters are required since the relief of the *Campo de Cartagena* is flat. Table 1 summarizes the characteristics of the different devices that have been developed and deployed on the farm.

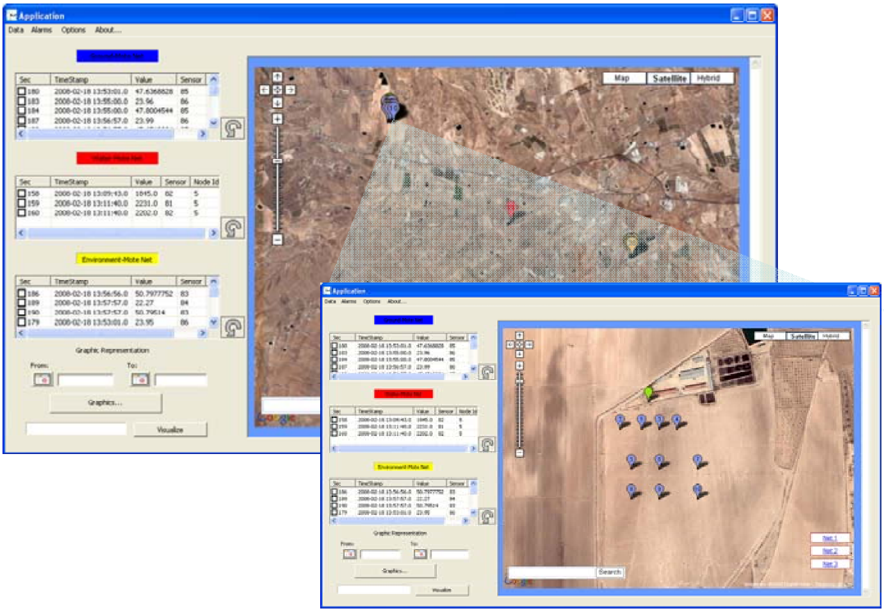
Table 1. Type of devices developed for the farm

Device	Function	µC/O.S.	Energy Source	Common Module (Range)	Sensors
Water Mote (Prototype)	Instantly measures water salinity and temperature	MSP430F1611 TinyOS 2	Rechargeable Battery	XStream (16 km)	EC 250 (Stevens)
GAIA Soil Mote (final product)	Instantly measures soil moisture, conductivity, salinity and temperature	MSP430F1611 TinyOS 2	Rechargeable Battery	CC2420 (230 m)	Hydra Probe II (Stevens)
Environ. Mote (Prototype)	Instantly measures relative humidity and temperature	MSP430F1611 TinyOS 2	Rechargeable Battery	CC2420 (230 m)	SHT71 (Sensirion)
Data-Sink/Gateway. (Prototype)	Links soil and environmental motes with repeater	MSP430F1611 TinyOS 2	Solar Cell + Rechargeable Battery	CC2420 (230 m) XStream (16 km)	N/A
Base Station (Prototype)	Links WSNs with software application	N/A	Grid	XStream (16 km)	N/A

4 Monitoring Application

The monitoring application consists of: (1) a graphical user interface (GUI) where the data read by the sensors are shown, and (2) a program that receives and stores data from the nodes. Both programs were developed using the Java programming language, with the Eclipse environment and the MySQL relational data base management system. The essential features of these applications as developed may be summarized as follows:

1. The GUI includes the placement of devices using the utility supplied by Google Maps. In this way we can identify the exact geographic position of each node and the crop in which it is located (see Figure 6).
2. 2. The data read by the sensors are sent periodically to the base station and stored in the data base (the program waits for an event indicating data available at the serial port). The GUI will read these data and visualize them graphically in real time. In addition, the sampling period can be modified from the user application.
3. The data base includes details of the nodes deployed, their regional aggregations, the sensors integrated in every node, the historical record of readings, the types of sensors, and the history of alarms received from the sensors and regions (for example battery failure, values below a threshold, etc.).



Ground-Mote Net

Sec	TimeStamp	Value	Sensor
☐ 180	2008-02-18 13:53:01.0	47.6368828	85
☐ 183	2008-02-18 13:55:00.0	23.96	86
☐ 184	2008-02-18 13:55:00.0	47.8004544	85
☐ 187	2008-02-18 13:56:57.0	23.99	86

Water-Mote Net

Sec	TimeStamp	Value	Sensor	Node Id
☐ 158	2008-02-18 13:09:43.0	1845.0	82	5
☐ 159	2008-02-18 13:11:40.0	2231.0	81	5
☐ 160	2008-02-18 13:11:40.0	2202.0	82	5

Environment-Mote Net

Sec	TimeStamp	Value	Sensor
☐ 186	2008-02-18 13:56:56.0	50.7977752	83
☐ 189	2008-02-18 13:57:57.0	22.27	84
☐ 190	2008-02-18 13:57:57.0	50.79514	83
☐ 179	2008-02-18 13:53:01.0	23.95	86

Fig. 6. Main view of monitoring application

A menu bar at the top provides the options noted above (see Figure 6). On the right of the screen a Google Map has been used to depict the geographic position of the deployed nodes. On the left there are three tables displaying the latest data readings from the sensors for the three networks shown on the right. Below the tables is a graphic display of the data for a user-selected time interval, or the latest data gathered.

The soil and environmental motes provide the following services: change the sensor sampling period and configure the device to send data from the battery every hour. They also trigger an alert signal if the battery charge is critically low. Moreover, the soil mote also provides other services, such as: set soil type, configure data measurement sets, set water constant and establish warm-up time. Note that all these services use a special combination of the data sent to set the sampling period.

5 Experimental Results

Two sensor networks were deployed in two plots of approximately 4 ha each. The plots are about 5.2 and 8.7 km respectively from the farm offices. Ten GAIA Soil-Motes, one Environmental-Mote and one Data-Sink/Gateway were deployed on each of the plots. The Data-Sink/Gateway was connected to an exterior 3 dBi omni-directional antenna placed on a post 5 m tall. This was to assure direct line-of-sight between the antennas of the ground-level Motes and the Data-Sink/Gateway. And again to assure line-of-sight between the Data-Sink/Gateway and the offices, one 15 dBi omni-directional antenna was placed on the office roof (9 m high), and another identical antenna on the Data-Sink/Gateway. Wireless communication between the rooftop antenna and the Base Station was achieved with a repeater. At the same time, a technology similar to that of the Data-Sink/Gateway was used to develop a wireless node (Water-Mote) to monitor the quality of the water supplied to the crop using the EC250 sensor.

A monitoring application, running on the Base Station, was developed to control all the devices and keep a record of the information received. It consists of: (1) a graphical user interface (GUI) where the data read by the sensors are shown using the utility supplied by Google Maps, and (2) a program that receives and stores data from the nodes. Both programs were developed using the Java programming language, with the Eclipse environment and the MySQL relational data base management system.

The trials were conducted on crops of Broccoli (Brassica oleracea L. var Marathon) covering an area of 4 ha each, located in *Campo de Cartagena* (37º44’26’’N, 1º13’38’’W) in south-east Spain. The seedlings were transplanted (with a population density of 5 plants/m2) on 10 November 2008 and the crop was harvested 12 weeks later, in the first week of February 2009. The soil characteristics of the crop at a depth of 40 cm were: clay loam texture, total carbonates 35.4 p.100, P(Olsen) 78.6 ppm, K(Ac-NH4) 487.0 ppm. A drip irrigation system was laid between the two rows of crops and 1 l/h emitters were installed every 0.20 m. Fertilizer was applied to the crop using fertirrigation. The nodes were deployed in the second week of November, at which time the owners of the farm began to gather data from the WSNs. The Soil-Mote sensors were placed at depths of 20 cm and 40 cm. During this time there was 198 mm cumulative rainfall, moderately strong winds of up to 69 km/h and mild temperatures (average 11.5 ºC). Figure 7 shows the data (soil moisture) collected over a twelve-week period. The Hydra Probe sensors provide accurate soil moisture measurements in units of water fraction by volume (wfv or m3m-3)—that is, a percentage of water in the soil displayed in decimal form. For example, a water content of 0.20 wfv means that a one-litre soil sample contains 200 ml of water. Full saturation (all the soil pore spaces filled with water) typically occurs between 0.5-0.6 wfv and is quite soil dependent. The nodes were found to function properly. This provides some assurance of the robustness of the arrangement for similar weather conditions.

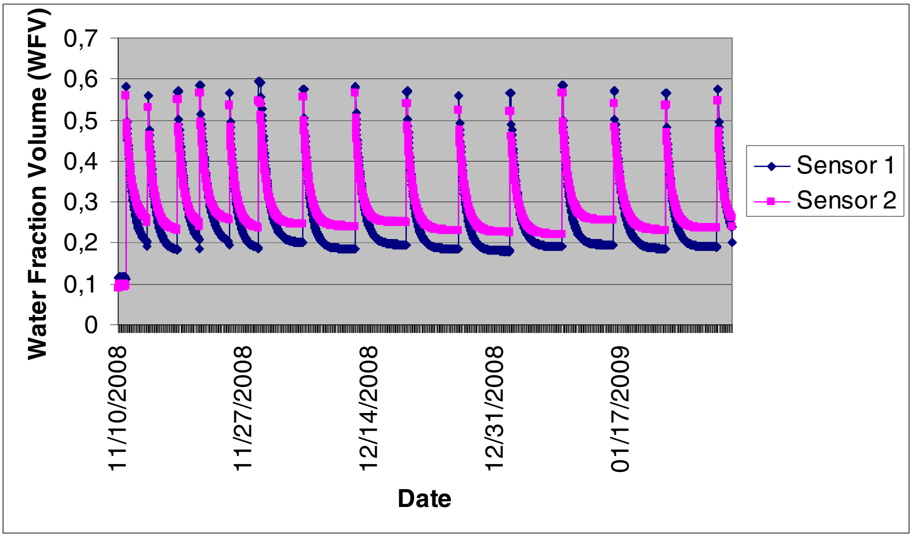


Fig. 7. Humidity data from one of the motes

Before this technology was introduced, the company monitored its crops in the traditional way—that is, a person visited the crop and the pond to measure the relevant agronomic parameters with appropriate portable equipment. Now, with the technology that has been developed, crop variables can be ascertained in real-time, and as a result the water requirements of the crops can be estimated without anyone having to visit them. The farm team were able to check, in real-time, that the optimum conditions for Broccoli growing were being maintained (salinity in the range 2-4 mmhos/cm, temperature between 10 ºC and 24 ºC, and relative humidity in the range 60%-90%).

6 Final Remarks and Conclusions

A sensor network was installed on a real farm in the *Campo de Cartagena*. To that end a set of specialized motes (GAIA Soil-Mote, Environmental-Mote and Water-Mote) were developed for different types of sensors. In turn, a set of auxiliary devices needed to implement the network (Data-Sink/Gateway, Repeater and Base-Station) were also developed. All the devices are available in prototype form, except for the GAIA Soil-Mote, which has been designed and manufactured as a commercial product that is robust enough for use in agricultural applications. The mote comes with a SDI-12 interface and its software is designed to handle two HP2 sensors connected to this interface. The software is readily adaptable to any other type of SDI-12 sensor. To check that they function properly, they were used for 10 weeks on a farm owned by the firm Langmead España S.L. in *Campo de Cartagena* in south-east Spain. The results were entirely satisfactory.

A new hardware device has been developed with the following advantages:

1. Low cost if compared with similar solution products.
2. It offers an SDI-12 communication interface, which is not provided in other commercial solutions.
3. New sensors can be easily connected by adding other general interfaces (SDI-12, 4-20 mA, 0-2.5 V), as in the case of the Environmental-Mote and the Water-Mote.
4. Wireless devices avoid the problems related to wired sensor networks deployed in crops.
5. The size of the network can be increased easily in comparison to wired solutions.
6. By using a Base-Station to gather sensor data it is possible to access, via the Internet, all stored data. This improves maintenance tasks because an in-situ data collecton is avoided.
7. The battery replacement is managed remotely. The system sends a signal to the user when the battery is low.

We are now working on an improved version of the GAIA Soil-Mote. In this version the idea is that the mote should be easy to configure in the factory for use as a mote or as a gateway. Similarly, the number and type of output interfaces has been increased (SDI-12, 4-20 mA, 0-2.5 V) so that they can also be factory-configured depending on the sensors that are to be connected to the mote. The purpose of factory-configuration is to keep manufacturing costs down by minimizing the number of components required for each configuration. And finally, we would note that a single-output connector has been designed for connection with external instruments, updating of firmware and battery recharging so that the mote does not have to be opened.

Acknowledgements

The authors wish to thank the Ministry of Industry, projects RIMSI (FIT-330100-2006-173) and ESNA (ITEA 2006), Fundación Séneca of the Murcia Region (ref ID-02998/PI/05) and the CICYT MEDWSA (ref TIN1006-15175-C05-02), Ministry of Education and Science, Spain, for supporting this work. They also gratefully acknowledge the supply of components by Texas Instruments and Maxim for our planned network deployment.

References

1. Zhang, N., Wang, M., Wang, N.: Precision agriculture a worldwide overview. Comput. Electron. Agric. 36, 113–132 (2002)
2. Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., Cayirci, E.: Wireless sensor networks: a survey. Comput. Netw. 38, 393–422 (2002)
3. Camilli, A., Cugnasca, C.E., Saraiva, A.M., Hirakawa, A.R., Corrêa, L.P.: From wireless sensor to field mapping: Anatomy of an application for precision agricultura. Comput. Electron. Agric. 58, 25–36 (2007)

4. Pierce, F.J., Elliot, T.V.: Regional and on-farm wireless sensor networks for agricultural systems in Eastern Washington. Comput. Electron. Agric. 61, 32–43 (2008)
5. Morais, R., Fernandes, M.A., Matos, S.G., Serodio, C., Ferreira, P.J.S.G., Reis, M.J.C.S.: A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture. Comput. Electron. Agric. 62, 94–106 (2008)
6. López Riquelme, J.A., Soto, F., Suardíaz, J., Sánchez, P., Iborra, A., Vera, J.A.: Wireless Sensor Network for precision horticulture in Southern Spain. Comput. Electron. Agric. (2009), doi:10.1016/j.compag.2009.04.006
7. IEEE Standard for Information Technology-Telecommunications and information exchange between systems-Local and metropolitan area networks- Specific requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs). 1st Ed.; IEEE Standard Association, Piscataway, NJ, USA (2006)
8. A Serial-Digital Interface Standard for Microprocessor-Based Sensors. Version 1.3 (July 18, 2005). Prepared By SDI-12 Support Group (Technical Committee). USA (2005), `http://www.sdi-12.org/` (accessed 10 March 2009)
9. López, J.A., Soto, F., Sánchez, P., Iborra, A., Suardiaz, J., Vera, J.: A. Development of a Sensor Node for Precision Horticulture. Sensors 9(5), 3240–3255 (2009)
10. Hill, J., Szewczyk, R., Woo, A., Hollar, S., Culler, D., Pister, K.: System architecture directions for networked sensors. Architectural Support for Programming Languages and Operating System. ACM SIGPLAN Notices 35, 93–104 (2000)
11. Gay, D., Levis, P., von Behren, R., Welsh, M., Brewer, E., Culler, D.: The nesC Language: A Holistic Approach to Network Embedded Systems. In: Proc. of the ACM SIGPLAN Conference on Programming Language Design and Implementation, San Diego, California, USA, pp. 1–11 (2003)