COMPUTERS AND ELECTRONICS IN AGRICULTURE 62 (2008) 94–106

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/compag

A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture

Raul Morais[a,b,*], *Miguel A. Fernandes*[b], *Samuel G. Matos*[b], *Carlos Serôdio*[a,b], *P.J.S.G. Ferreira*[c], *M.J.C.S. Reis*[a,b]

[a] *Centro de Estudos Tecnológicos, do Ambiente e da Vida (CETAV), UTAD University, Quinta de Prados, 5001-801 Vila Real, Portugal*
[b] *Departamento de Engenharias, Universidade de Trás-os-Montes e Alto Douro (UTAD), Quinta de Prados, 5001-801 Vila Real, Portugal*
[c] *Signal Processing Laboratory (SPL), Department Electrónica, Telecomunicações e Informática/IEETA, Universidade de Aveiro, 3810-193 Aveiro, Portugal*

ARTICLE INFO

Article history:
Received 28 June 2007
Received in revised form
29 November 2007
Accepted 3 December 2007

Keywords:
ZigBee
Wireless sensor network
Viticulture
Acquisition device
Remote sensing
Energy harvesting

ABSTRACT

This paper is part of a long-term effort to introduce precision viticulture in the region of Demarcated Region of Douro. It presents the architecture, hardware and software of a platform designed for that purpose, called MPWiNodeZ. A major feature of this platform is its power-management subsystem, able to recharge batteries with energy harvested from the surrounding environment from up to three sources. It allows the system to sustain operation as a general-purpose wireless acquisition device for remote sensing in large coverage areas, where the power to run the devices is always a concern. The MPWiNodeZ, as a ZigBee^{TM} network element, provides a mesh-type array of acquisition devices ready for deployment in vineyards. In addition to describing the overall architecture, hardware and software of the monitoring system, the paper also reports on the performance of the module in the field, emphasising the energy issues, crucial to obtain self-sustained operation. The testing was done in two stages: the first in the laboratory, to validate the power management and networking solutions under particularly severe conditions, the second stage in a vineyard. The measurements about the behaviour of the system confirm that the hardware and software solutions proposed do indeed lead to good performance. The platform is currently being used as a simple and compact yet powerful building block for generic remote sensing applications, with characteristics that are well suited to precision viticulture in the DRD region. It is planned to be used as a network of wireless sensors on the canopy of vines, to assist in the development of grapevine powdery mildew prediction models.

1. Introduction

Precision agriculture (PA) and precision viticulture (PV) are production systems that promote variable management practices within a field according to site conditions. The concept is based on new tools and information sources provided by modern technologies, such as yield monitoring devices, soil, plant and pest sensors and remote sensing. Despite the benefits, such diversity is currently restraining the rate of adoption of these technological tools, which varies considerably from

---

* *Corresponding author at*: Centro de Estudos Tecnológicos, do Ambiente e da Vida (CETAV), UTAD University, Quinta de Prados, 5001-801 Vila Real, Portugal. Tel.: +351 259 350 372; fax: +351 259 350 300.

E-mail addresses: rmorais@utad.pt (R. Morais), miguelseia@gmail.com (M.A. Fernandes), smatos@utad.pt (S.G. Matos), cserodio@utad.pt (C. Serôdio), pjf@ua.pt (P.J.S.G. Ferreira), mcabral@utad.pt (M.J.C.S. Reis).

0168-1699/$ – see front matter
doi:10.1016/j.compag.2007.12.004

country to country, and from region to region (Seelan et al., 2003).

The Demarcated Region of Douro (DRD) (a UNESCO World Heritage Site and the oldest Wine Demarcated Region of the World), due to its unique characteristics, poses very specific challenges, mainly due to the topographic profile, pronounced climatic variations and complex soil characteristics. Grape harvest and disease predictions as well as the assessment of the grape value are currently left to the grape growers, without the help of decision-support mechanisms, in an environment where no significant irrigation systems exists. In order to improve the quantity and quality of winegrowers' products, an array of sensors that monitors the environmental, climatic and physiological parameters is needed.

The on-going technological developments in the miniaturization of electronic devices and wireless communication technology have led to the emergence of Wireless Sensor Networks (WSN). The power necessary to effectively run the related circuitry is currently being scaled down, with the help of energy harvested from the environment where the devices are deployed. Strictly speaking, WSN are arrays of electronic devices with sensing capabilities that are interconnected using a radio network. Many architectures exist, ranging from micro-devices with embedded smart sensors to complete self-powered acquisition devices that support a large variety of external sensors (Morais et al., 1996; Gomide et al., 2001; Beckwith et al., 2004; Delin et al., 2005; Hart and Martinez, 2006). Regarding network support, many protocols such as Bluetooth, ZigBee and proprietary forms of radio network interconnections exist (Lee et al., 2002; Beckwith et al., 2004; Wang et al., 2006).

There are several key issues to address when selecting a suitable technology for wireless data transfer. One of the most important criteria is the network support, usually determined by the application target, which limits the available offer. Other key factors include data transfer rates and power consumption. Many stand-alone radio-frequency transceivers are suited for cable replacement (point-to-point connections), often using proprietary protocols to enhance data transfer reliability. However, in these RF devices, mesh-type networks are usually not supported due to the complexity of the software implementation.

The well known IEEE 802.11 family of standards is able to handle very high data rates, which however imply power-demanding devices. The IEEE 802.15.1 (Bluetooth) standard, although capable of supporting a Personal Area Network (PAN), is primarily intended for cable replacement solutions. It does have the capability to form small star-type networks known as piconets and scatternets. Within these networks, a master device performs synchronisation between all connected slaves, rendering high data rates and continuous data transfers possible. Although interesting to deal with a limited number of nodes, it has not been widely adopted for the deployment of large arrays of sensing devices in crops, mainly due to power demands and restrictions on the number of nodes and connections.

In contrast, the ZigBee environment has been specifically developed to address the demands of sensor networks, including the need to handle a large number of nodes. ZigBee builds upon the physical (PHY) and medium access control (MAC) layers defined by the IEEE 802.15.4 standard (IEEE, 2003), enabling the creation of complex ad hoc networks with up to 65536 devices, suitable for industrial, agricultural, vehicular, residential and medical environments. The intent of IEEE 802.15.4 is to provide ultra low power consumption and very short wake-up times capabilities at very low cost to devices operating in a Low Rate (250 kbps) Wireless Personal Area Network (LR-WPAN). To this effect, the IEEE 802.15.4 assumes that the data transmitted are short and that transmissions occur at a low-duty cycle (active/sleep times ratio), reducing the overall power needs and enabling the application of battery–powered embedded systems.

The ZigBee standard defines the network layer specification to allow the formation of three network topologies: star, tree and peer-to-peer. In the latter topology, also known as mesh-type, every network element can communicate with any other within its range. This allows more complex network formations to be implemented, such as ad hoc and self-configuring networks. These should contain a unique coordinator, responsible for managing all the PAN functionalities and, for instance, retrieving all relevant data from the ZigBee network. This mesh-type topology, which relies on the routing mechanisms for multi-hop provided by the network layer, is a key element for wireless networks of smart acquisition devices in the field. ZigBee also defines the type of device based on the set of functions that is enabled to perform. The Full-Function Device (FFD) can act as a router while the Reduced-Function Device (RFD) is usually an end-device that is only allowed to communicate with its router or coordinator. In addition, ZigBee also provides a framework for application programming in the application layer. More details on ZigBee/802.15.14 networks can be found in the survey (Baronti et al., 2007) and in (IEEE, 2003).

Currently, ZigBee is a promising solution to enhance the development of ad hoc multi-hop sensor networks, and a lot of research effort is being invested in adopting and finding new solutions for almost every kind of monitoring purpose (Jinsheng et al., 2006). However, agricultural production systems suffer from the usual delay in the application of these highly innovative technologies. Among the several aspects that constrain these developments we mention the issues related to power management and availability, and the ease with which the systems can be deployed in an open field.

This paper addresses some of these challenges and describes a ZigBee multi-powered wireless acquisition device, designed to be part of the remote sensing project of introducing PV in the Demarcated Region of Douro. The system represents an evolution over the SPWAS (Morais et al., 1996) acquisition station, contributing to make highly flexible acquisition systems available for application in PV and remote sensing. Its features include the ability to harvest energy from the environment, in multiple ways. It also contains a software-based method that prevents automatically switched-off nodes from being switched-on soon after, as their batteries charge again. Such cycles have a negative impact on the battery life, and are more difficult and expensive to avoid via hardware. The need to deal with network discovery/connectivity failures and avoid repetitive and wasteful connection attempts is also addressed.

The paper describes the overall architecture of this monitoring system (Section 2), then the hardware (Section 3) and software (Section 4) of the basic module around which the system is built, and then reports on the performance of the module in the field, emphasising the energy issues, which are crucial to obtain self-sustained operation. This is the main experimental part of the paper (Section 5), and the results obtained confirm that the hardware and software solutions proposed in the paper do indeed lead to good performance. The conclusions and lessons that were learned in the process are discussed in detail in Section 6, which closes the paper.

2. Remote sensing wireless network for precision viticulture

The layout of hillside vineyards in the DRD is strongly conditioned by the original slope and relief of the parcels of vines. Also, the soil is mainly based on complex schist which imposes some constrains in the assessment of its hydrological aspects. The unique characteristics of these vineyards, as well as the topographic aspects, erosion control, vertical planting, the intrinsic limited water availability, and wide temperature span across all day and year, demand the most recent technological tools, such as distributed monitoring and information processing. These may help in understanding vineyard variability and therefore how it might be managed, thus improving the quantity and quality of the wines. A good example of using WSN as a key tool to understand productivity variability can be found in Camilli et al. (2007). As an increasing number of electronic devices with various types of sensors are embedded in agricultural processes, efficient system integration has become a critical goal. The huge amount of data retrieved by intensive field data acquisition needs to be centralized and made available on the web, by using for instance geographical information systems (GIS). On a regional, or even at a global scale, large plantation infrastructures are the result of the interconnection of multiple local plantations, which is the DRD dominant scenario regarding vineyards.

Such a distributed platform, which incorporates information from remote sensing, from in situ weather conditions, from water source levels, from soil history, and from farmer knowledge about the relative productivity of selected “Management Zones” of the vineyard, can be applied, for instance, to predict yield and diseases, and to disseminate advice throughout the growing season about the optimum usage of water and the chemical treatments needed.

To address the relevant issues regarding the deployment of such a monitoring network in the DRD with its specificities, we propose a remote sensing network architecture, depicted in a simplified way in Fig. 1. The MPWiNodeZ, as a self-sustaining smart acquisition device, aims to enhance in-field data gathering and to give network support to systems such as those described in (Valente et al., 2006). For each vineyard management zone (VMZ), a ZigBee network of MPWiNodeZ devices can be deployed to acquire data on soil moisture content, soil temperature, air temperature, relative humidity and solar radiation, among other parameters. The cluster head (CH) operates as a local (or VMZ) sink node for this wireless sensor network. This creates an intermediate level of aggregation nodes that manages the sensor networks and performs local data integration and supervision functions, while maintaining connectivity through the whole region.

Since each wine making company may have vineyards located in any location of the DRD, the connectivity between each VMZ and the company office headquarters (shippers’ office in Fig. 1) represents an important issue that must be addressed. To this effect, the clusters are wirelessly linked to the shippers’ office through a TCP/IP-based connection such as GPRS and 802.11 links.

To accommodate the disparate data sources from vineyards and its surrounding environment, each acquisition device should also have a high degree of flexibility concerning the types of sensors allowed. To accomplish this goal, the common signal conditioning procedures of acquiring voltage-, current-, frequency- and resistance-output sensors have been complemented with a small set of IEEE 1451 standards to include information about each sensor in a Transducer Electronic Data Sheet (TEDS). Each acquisition device has the necessary computing power to verify and validate its own data and convert them to international units, thus reducing the amount of processing at the aggregation node that could have hundreds of devices connected.

Fig. 2 illustrates the application of a ZigBee network to enhance remote sensing in a PV environment. For simplicity, only one parameter is shown for each network element. In the case of the MPWiNodeZ device, up to nine parameters can be measured. The experimental results reported in this paper show that the power management and networking solutions adopted do work in practice, both in the laboratory and in the field. The MPWiNodeZ devices will be used to deploy a network of wireless sensors on the canopy of vines, which will be used as a tool to develop models to predict the development of grapevine powdery mildew.

3. The MPWiNodeZ acquisition device

In order to better understand various issues in deploying a wireless sensor network in remote sensing of environmental parameters, we have developed a prototype system that satisfies the requirements for self-sustaining network nodes in agricultural environments. The MPWiNodeZ (Multi-Powered Wireless Node ZigBee) device is a small custom board aimed to act as a router or as an end-device in ZigBee networks. It is based on the MPWiNodeX, a generic power-management platform that enables self-sustaining devices. A similar device, denoted MPWiNodeS, based on an off-the-shelf RF transceiver (RC1280 from Radiocrafts, Norway), has also been developed and tested to enable simple star-type networks on a proprietary environment with the main purpose of evaluating and characterizing the power-management platform. The MPWiNodeZ can manage up to three simultaneously energy sources to charge a compact pack of three 1/2 AA-size 650 mAh NiMH batteries.

The MPWiNodeZ is built around two varieties of waterproof encapsulations to support the harsh environment that an open field presents to any electronic device. The power-

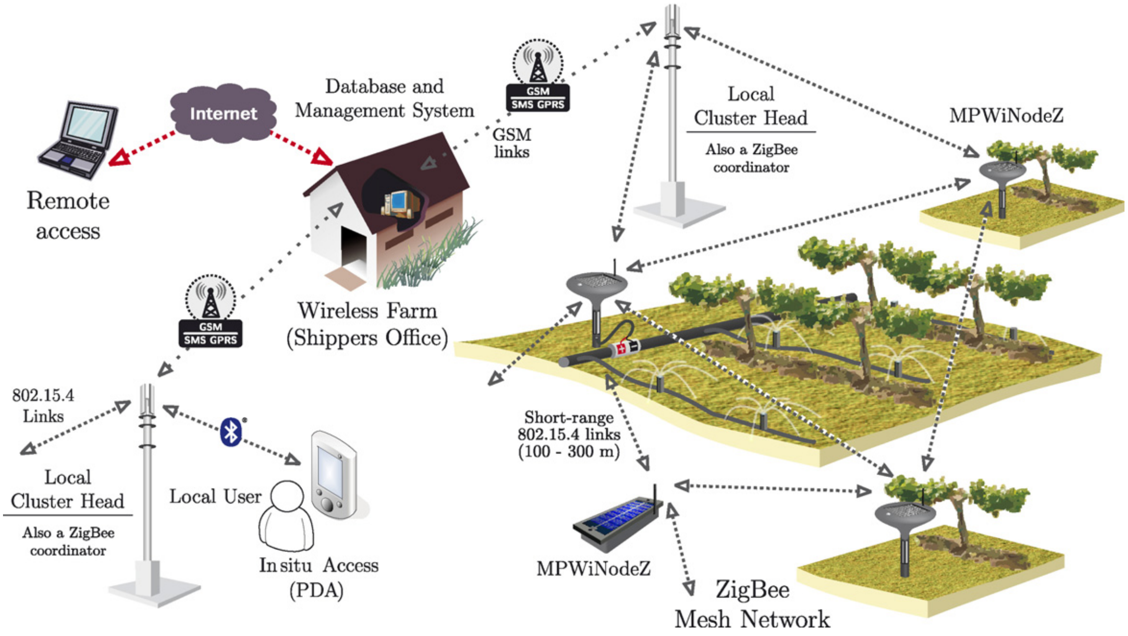

Fig. 1 – Illustration of the on-going implementation of an *in-field* data acquisition network, based on a ZigBee network of MPWiNodeZ devices in a precision viticulture environment.

management hardware and software systems were carefully designed to withstand the operating conditions. To achieve maximum flexibility, the system recharges its batteries using energy harvested from the surrounding environment, from up to three sources (photonic energy, kinetic energy from moving water in irrigation pipes and from wind), avoiding maintenance and human interference. The MPWiNodeZ device combines these energy harvesting methods with a power-conservative software application that avoids the repetitive use of the available radio channels when joining an existent network, thus extending battery autonomy. The embedded software application is ready for the implementation of the IEEE 1451 object model to achieve a higher degree of sensor interoperability.

The core of the MPWiNodeZ is a wireless μ-controller (JN5121 from Jennic, UK) that comprises an 802.15.4 RF transceiver and the ZigBee stack. Besides the embedded communications capabilities, this platform has also been chosen to provide reliable signal conditioning to raw sensors and subsequent data processing. To this effect, it is intended to employ a scaled-down version of the IEEE 1451.1 object model for smart sensors, thus promoting a well-defined communication protocol for high-level sensor-to-network interaction.

3.1. *Hardware overview*

The MPWiNodeZ device offers a rich and flexible set of functions that enables a wide range of sensors to be plugged in, regardless of its computation and communication capabilities with minimal power consumption. By employing the IEEE 1451.1 object model, the MPWiNodeZ device can use this standardized procedure to convert raw data from low-cost analog sensors into meaningful information. The same approach has also been followed in Oostdyk et al. (2006) and Ding et al. (2007), where the implementation of the IEEE 1451 has been simplified to a high-level communication between two ZigBee devices (the coordinator and the MPWiNodeZ), each one acting as a Network Capable Application Processor (NCAP).

The JN5121 wireless μ-controller has been chosen as a cost-effective solution. This highly integrated device integrates a 32-bit RISC processor, with a fully compliant 2.4 GHz IEEE

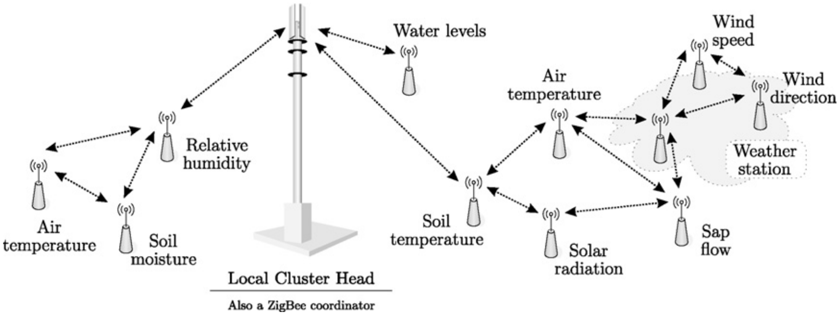

Fig. 2 – Deployment of a wireless sensor network based on a ZigBee mesh-type topology for environment monitoring purposes.

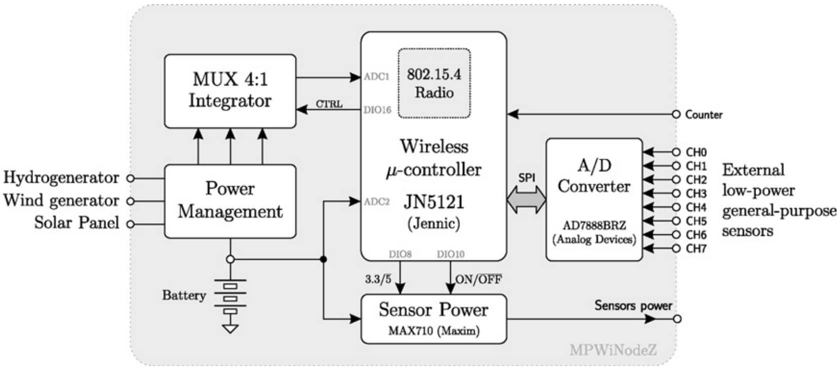

Fig. 3 – MPWiNodeZ hardware architecture.

802.15.4 transceiver, 64 kb of ROM, 96 kb of RAM, and incorporates a wide range of digital and analogue peripherals. With a low sleep current (below 5 μA), the JN5121 provides a versatile solution for wireless sensor networking applications.

The block diagram of the MPWiNodeZ device is depicted in Fig. 3. Besides the μ-controller, it comprises an external 12-bit, A/D converter (AD7888 from Analog Devices, MA, USA). The AD7888 is a micro-power (3 μW in power-down mode) ADC with serial interface that operates from a single 2.7 V power supply. It contains eight single-ended analog inputs and features an on-chip 2.5 V precision reference that may be used (software selectable) for the voltage reference for A/D conversion instead of using the supply voltage. The power-management block is responsible for charging the system battery-pack and additionally it provides data on energy harvested from environment. External sensors are powered by a separate DC–DC converter (MAX710 from Maxim, CA, USA) that converts the battery voltage into a regulated 5 V or 3.3 V output, pin selectable. This converter is turned on only when needed, otherwise it remains in the shutdown mode. A photograph of the MPWiNodeZ device can be seen in Fig. 4.

3.2. *Energy harvesting and power management*

When considering an array of sensing devices that are deployed across an extensive agricultural area, the energy supply system is a crucial issue. The traditional, yet most used approach is to use batteries, rechargeable or not. However, these energy reservoirs can store a finite amount of energy, and their replacement and maintenance represents a severe bottleneck. An emerging technique that circumvents this limitation is environmental energy harvesting that exploits energy sources that are ubiquitous to the operating space (Raghunathan et al., 2006). In the present application target, and regarding availability, the most feasible harvesting techniques are related to solar and kinetic energy sources.

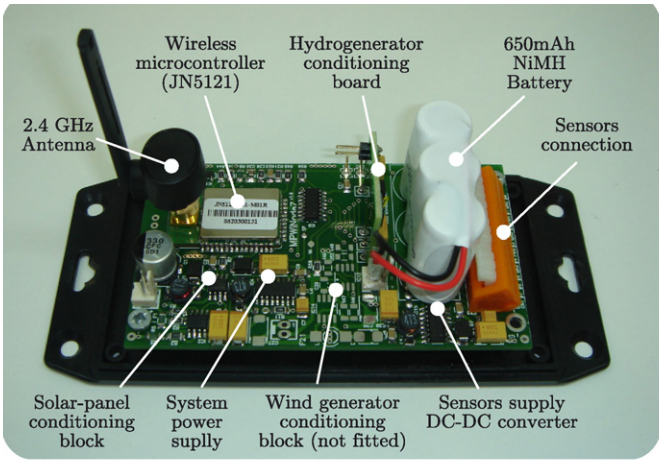

Fig. 4 – Photograph of an MPWiNodeZ device.

The power requirements of the MPWiNodeZ device are mostly satisfied by a low-voltage 0.5 W solar panel (MSX005 from Solarex, MD, USA), which is used to efficiently charge a compact 3.6 V 650 mAh NiMH battery-pack. With only this energy source and reservoir, the MPWiNodeZ would operate indefinitely, due to its low-duty cycle operation as a ZigBee end-device. However, this turns out to be insufficient to permanently run a device operating as a network router. To this effect, supplementary kinetic energy is harvested from water and wind flow. In the first case, power is provided by a hydrogenerator placed in the irrigation pipes (which we regard as being similar to a power outlet in the field) and, in the second case, by a small wind-powered generator. Fig. 5 shows photographs of the energy harvesters that have been used.

In addition to providing power, the associated harvesting techniques double as sensors, yielding data on the amount of solar radiation, water flow and wind speed. Fig. 6 shows the simplified power-management block where, besides the main function of recharging the system battery, it also supplies data on the amount of solar radiation, wind speed and irrigation water flow as a density of pulses related with each parameter.

Each pulse sequence is applied to a 4:1 precision multiplexer (MAX4618 from Maxim, CA, USA), which selects the signal to be filtered (by R_1 and C_1 in Fig. 7), in order to generate its mean value. Prior to analog-to-digital conversion, this DC value is amplified by a factor of two, using a fixed-gain operational amplifier (MAX4174 from Maxim, CA, USA). Due to its low power consumption, this amplifier is simply powered from a digital output of the μ-controller. In addition, and since each power-management output signals are open-drain, the other part of the 4:1 multiplexer is used to connect the appropriate pull-up resistor. By using this approach, based on the use of the same components for all inputs, the related measurement chain can be disconnected thus saving energy.

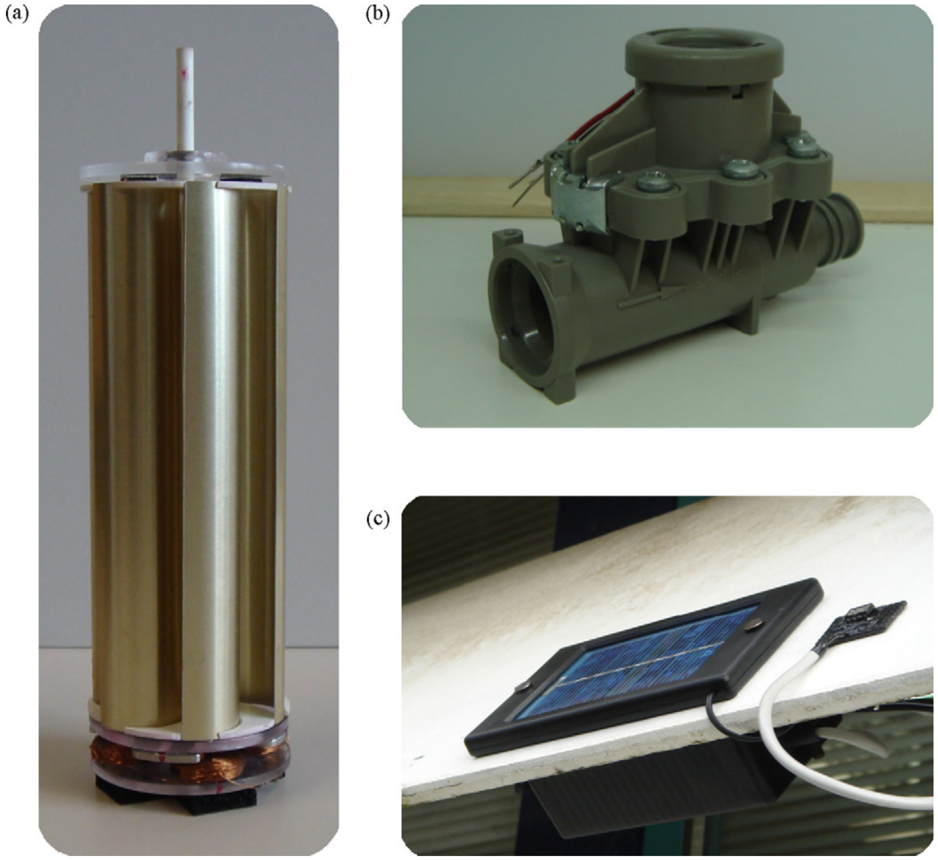

Fig. 5 – Energy harvesters of the MPWiNodeZ device: (a) the small (60 mm diameter by 200 mm height) 6-blade Savonious design wind generator; (b) the commercial hydrogenerator designed to be used in smart gas-based water heating appliances and (c) the 0.5 W low-voltage solar panel.

4. Software organization

The MPWiNodeZ was built around the ZigBee standard, to give wireless networking capabilities to the acquisition devices. Monitoring needs, regarding the hypothetical sensing devices that may be attached as well as the sampling interval required for each of them, have dictated the implementation of a high-level application protocol. For instance, every attached sensor may have different operating rules that must be transferred, stored and applied by each MPWiNodeZ device. In addition, power-management issues should be addressed to avoid any kind of unpredicted behaviour, such as unreliable battery operation.

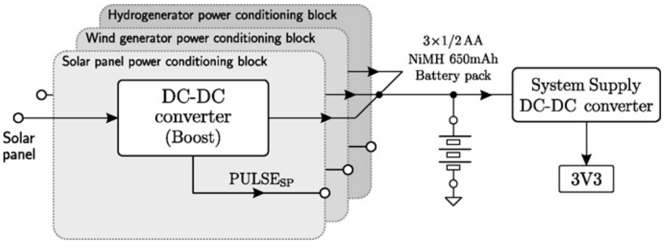

Fig. 6 – MPWiNodeZ simplified power-management block.

4.1. *Operation mode*

The software was designed to meet the demands of battery-operated systems. One major concern is the possibility of system oscillations, or more precisely system on and off cycles, caused by partially charged batteries. The cycles are usually triggered by a battery voltage drop, a consequence of nearly drained batteries. The voltage drop leads to the system being turned off. The battery voltage then rises again, because the load is removed, and the system may be switched on again, and so on. The traditional approach to prevent this undesirable oscillating situation is to add some hysteresis to

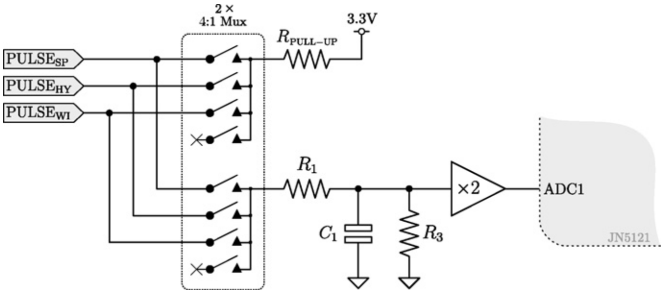

Fig. 7 – Analog processing of the power-management output signals.

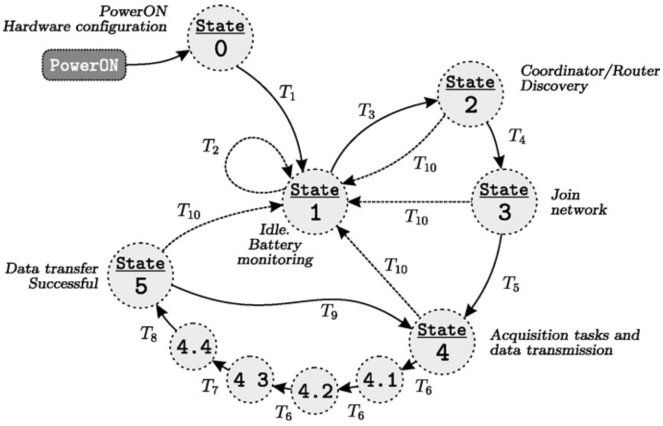

Fig. 8 – Overview of the MPWiNodeZ state machine implementation.

the power-management circuits. In the case of the MPWiNodeZ device, the solution was implemented in software, and completely avoids the oscillation problem.

The application code (developed under the Jennic CodeBlocks environment) that was implemented in MPWiNodeZ device follows the generic state machine represented in Fig. 8. After a power-on, the hardware is properly configured and left in a state of minimum current consumption, State 0. After this very first initialization stage, a sleep time T_1 is used before going to State 1.

State 1 represents the idle state where the battery voltage level is monitored. Every T_2 s, the system wakes-up and samples the battery voltage level. If the battery level is higher than a predetermined value, the system goes to State 2 after the sleep time T_3, otherwise remains in State 1. After switching to State 1, which means that the battery has enough energy, the MPWiNodeZ device tries to discover a nearby router or coordinator for binding. If successful, it is assumed that the acquisition device has the sufficient conditions to operate normally and tries, after the short time T_4, to join the existing ZigBee network (State 3) in order to acquire and store the network parameters for later use. If discovery and joining conditions are not met, it returns to the idle state after the sleep time T_{10}.

State 4 reflects the data acquisition and transmission tasks. The first time that the MPWiNodeZ device goes to this state (on the transition 3 → 4), it waits the fixed sleep time T_5. The sub-states 4.1, 4.2, 4.3 and 4.4 (separated by the time T_6) are responsible for setting the necessary timing tasks in the data acquisition process (sensors power-on time, capture period, etc.). At the end (sub-state 4.4), the 802.15.4 radio system of the μ-controller is powered on (T_7 interval) to send the acquired data using the saved network parameters. If an acknowledgement is received from the network layer (indicating that data has been transferred to the nearby router or coordinator), the MPWiNodeZ enters in sleep mode during the time T_9 that represents the time between data samples, user defined. In case of failure, it returns to State 1.

Besides the above-mentioned, states 1, 2, 3, 4 and 5 have additional conditions (dashed curves in Fig. 8), concerning battery voltage levels, that must be met. Whenever the battery voltage falls below a predetermined value, the MPWiNodeZ returns directly to the idle mode waiting for the battery to be operative. Table 1 shows these time intervals (used by default) and gives a short description for each one.

Table 1 – Time intervals typical values

Time interval	Value (s)	Description
T_1	10	Power-up to idle mode time
T_2	600	Battery monitoring time interval
T_3	120	Battery hysteresis time
T_4	2	Time allowed to join network
T_5	60	First acquisition interval
T_6	1	Acquisition timing tasks
T_7	0.1	Radio and protocol power-up time
T_8	3	ACK wait time
T_9	–	User defined time (by rules)
T_{10}	120	Jump to idle state time

4.2. *Functional rules and configuration*

One of the goals of the MPWiNodeZ device is to promote the on-board extraction of meaningful information about the raw sensors that can be connected. To this effect, and as a first step to adopt the IEEE 1451 family of standards concerning smart sensors, the 1451.0 definition of TEDS is used, mainly to convert raw data into metadata. As a result of this implementation, the MPWiNodeZ is able to perform some local processing tasks and return meaningful sensor data over the network such as the sensor value of the measured parameter in engineering units, rather than the unprocessed, raw result of an analog-to-digital conversion.

The TEDS is an electronic data sheet in a standardized format stored in the μ-controller flash memory that describes each attached transducer through the Transducer Interface Module (TIM). Since the MPWiNodeZ has a total input capability of 9 channels (8 analog inputs and a digital counter input), each channel in the TIM must be described. For that purpose, a channel TEDS was developed. It contains information of each transducer such as the transducer type, range limits, physical units and timing restrictions. In this first step to adopt IEEE1451, each channel TEDS was stored in the μ-controller flash memory only during the programming process. If some transducer attached to some input channel is changed, a new programming procedure is needed. In the near future, we intend to upload each TEDS through the wireless network.

Beside the characterization of each transducer, the behaviour of the entire MPWiNodeZ device should also be defined. In our implementation, it is defined by a set of functional rules. These rules occupies only four bytes (valid for MPWiNodeZ and MPWiNodeS devices), thus being suitable to upload through the ZigBee network. Table 2 shows the bit coding of these 4-byte rules, where a short description is also given.

These 4-byte rules settings virtually define the full-operation mode of each networked MPWiNodeZ device. Besides the usual procedure of enabling each data acquisition channel sampling and time window between each sampling procedure, they also allow other important settings such as the definition of the transmit power level that may be used. When in automatic mode, each MPWiNodeZ device uses the

Table 2 – The 4-byte rules that defines the MPWiNodeZ operation mode

Bit	Bit-coding	Default value	Short description
Rules 1-byte coding			
7	Counter timebase:1	0	Defines the frequency measurement time window
6	Counter timebase:0	1	Options are 50, 100, 150 and 200 ms
5	Average samples	1	Selects the average procedure to be applied. With this option, each sample = (6 burst acquisitions − min value − max value)
4	DCPulse Windgenerator	0	Measures the DC value of the wind generator pulses
3	DCPulse Hydrogenerator	0	Measures the DC value of the hydrogenerator pulses
2	Frequency Measurement	0	Selects a frequency measurement on the counter input
1	DCPulse SolarPanel	1	Measures the DC value of the solar-panel pulse output
0	Battery voltage acquisition	1	Measures the MPWiNodeX battery voltage
Rules 2-byte coding			
7	Supply voltage (MPWiNodeZ)	0	JN5121 function to measure power supply
6	On-chip temp. (MPWiNodeZ)	0	JN5121 function to measure on-chip temperature
5	Reserved for future use	0	
4	Reserved for future use	0	
3	Reserved for future use	0	
2	Reserved for future use	0	
1	Reserved for future use	0	
0	Reserved for future use	0	
Rules 3-byte coding			
7	ADCChannel#07 select bit	1	Acquire signal from the external ADC channel #07
6	ADCChannel#06 select bit	1	Acquire signal from the external ADC channel #06
5	ADCChannel#05 select bit	1	Acquire signal from the external ADC channel #05
4	ADCChannel#04 select bit	0	Acquire signal from the external ADC channel #04
3	ADCChannel#03 select bit	0	Acquire signal from the external ADC channel #03
2	ADCChannel#02 select bit	0	Acquire signal from the external ADC channel #02
1	ADCChannel#01 select bit	0	Acquire signal from the external ADC channel #01
0	ADCChannel#00 select bit	0	Acquire signal from the external ADC channel #00
Rules 4-byte coding			
7	TimeBetweenSampling:2	0	Defines the time interval between acquisition tasks (T_9).
6	TimeBetweenSampling:1	0	Options are 30, 60, 120, 300, 600 and 1800 s. During the
5	TimeBetweenSampling:0	0	selected interval, the system is in a low-power sleep mode.
4	DisableAcquisitionOnWake	0	No data is acquired—wakes regularly to eventually receive new rules.
3	TransmitPowerLevel:2	0	Definition of the transmit power level, ranging from the minimum to maximum in 6 steps and the auto-adjust option based on the RSSI information and LQI (Link Quality Indication).
2	TransmitPowerLevel:1	1	
1	TransmitPowerLevel:0	1	
0	Use TEDS information	1	With this option active, raw sensor data (ADC count) is converted to engineering units based on the corresponding TEDS metadata.

Link Quality Indication (LQI) of the wireless μ-controller to adjust the transmitted power, thus optimizing energy usage during each data transfer.

The identification of the sender also poses specific problems that must be addressed. When working with a mesh-type network topology, sender identification is not always possible (an example is when the sender is more than two hops from the coordinator). To overcome this issue, we have decided to transmit the sender identification along with sensor data. Fig. 9 shows the ZigBee protocol KVP (Key Value Pair) frame used in data transmission. Essentially, our ZigBee payload comprises the sender identification, the 4-byte device operating rules and data payload flowing between the MPWiNodeZ device and the network coordinator. This data payload field contains the data acquired from the attached sensors as well as the time stamp which will be discussed in the next section.

4.3. *Time stamp*

Time synchronization is a common requirement for wireless sensor networks since it allows collective signal processing, sensor and source localization, data aggregation, and distributed sensing (Milenković et al., 2006). In some applications of wireless personal area networks, synchronized time stamps are critical for proper correlation of data coming from different sensors and for an efficient sharing of the communication channel. Time stamping is also important in the case of intermittent communication within multi-hop networks that can significantly postpone transmission of the sensors' data.

Remote sensing in precision agriculture is one example of a networking sensing application where real-time requirements are not strict. Due to the process inertia, most of the measurements are commonly taken with a time base of several minutes, which relaxes the algorithms that provide a time

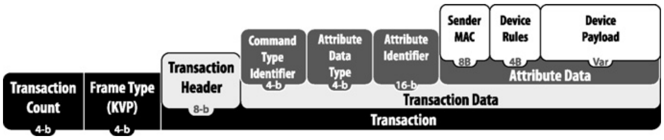

Fig. 9 – ZigBee Application Framework frame format used in the MPWiNodeZ device.

stamp for each data sample. Such time scales are appropriate for parameters such as air and soil temperature, relative humidity, soil moisture, solar radiation, precipitation, wind speed and sap flow. For the planned sensing network applications of the MPWiNodeZ device, the time stamps do not require precision of seconds; 1 min is a typical value.

The time stamp is usually tagged to a data sample by the ZigBee coordinator every time that a data frame is received. However, a more flexible mechanism has been added in order to support acquisition devices that have an embedded Real-Time Clock (RTC). The general idea is to add a time stamp as soon as possible, at the origin of the data if at all possible. If the MPWiNodeZ device uses a low-power RTC (in our case DS1302 from Dallas Semiconductor, CA, USA), a valid time stamp data is immediately transmitted to the coordinator. If not, the time stamp is reset to 0, indicating that the next node must insert it. A network router with RTC hardware capabilities may have to insert all the time stamps if none of the nodes have the mechanism for doing so. Otherwise, the insertion of the time stamp is left to the network coordinator. Fig. 10 illustrates the described process where the seconds field in the time stamp is used for illustration purposes only. In this example, device A takes some measurements at Coordinator Time (CT) 15:43:28. Since device A does not have a RTC, it simply clears the time stamp field. Device C, which has a RTC, receives the data payload at CT 15:43:36, inserting that time in the time stamp field. Finally, the data reaches the coordinator at CT 15:43:40, which inserts the samples values in the internal database with the 15:43 time stamp.

5. Experimental results

In order to properly evaluate the MPWiNodeZ device, a two-phase experimental methodology was used. It validates the power-management solutions during all active time periods (acquisition, processing, transmission and reception), and tests the operational issues regarding software implementation of the state machine under critical network conditions.

The first phase took place in a controlled laboratorial environment, where a small ZigBee network was formed by using a coordinator (connected to a laptop through a RS232 link), two network routers (one hop away from the coordinator) and two MPWiNodeZ devices (as the one shown in Fig. 4) as end-devices, each connected to its router.

The second experimental phase was performed under real operating conditions in a nearby vineyard. To this effect, an MPWiNodeZ was used to acquire air and soil temperature, relative humidity and solar radiation data, as depicted in Fig. 11. To test the discovery and joining procedures of the ZigBee application framework, two routers (actually two MPWiNodeZ devices running the router application software) were used in between the MPWiNodeZ under test and the coordinator (located in the laboratory).

The main goal of the first stage experiments was the validation of all software solutions, including the described state machine and the evaluation of the power-management platform in low-duty cycle operation modes and under critical situations, such as the power-up conditions after a battery charging cycle has been initiated. The handling of these situations usually requires a large amount of power that we needed to quantify and measure, especially when running network discovery/joining procedures. Because this first stage of the experimental setup exercises the system under particularly severe conditions, it provides important insight about the deployment of ZigBee-based systems running on batteries charged from energy harvested from the surrounding environment. In order to take proper and representative waveforms of battery voltage and current consumption profiles, this evaluation had to be performed in the laboratory. To best describe real operating conditions, several low-power analog sensors were used: three temperature sensors for measuring two air and one soil temperature (LM60B from National Semiconductor, CA, USA), one relative humidity sensor (HybridCap from Panametrics, USA) and two solar radiation sensors (TSL251 and TSL230 both from Texas Instruments, USA). The sampling rate of acquired data was kept randomly variable between 30 s and 30 min to create several battery discharging profiles.

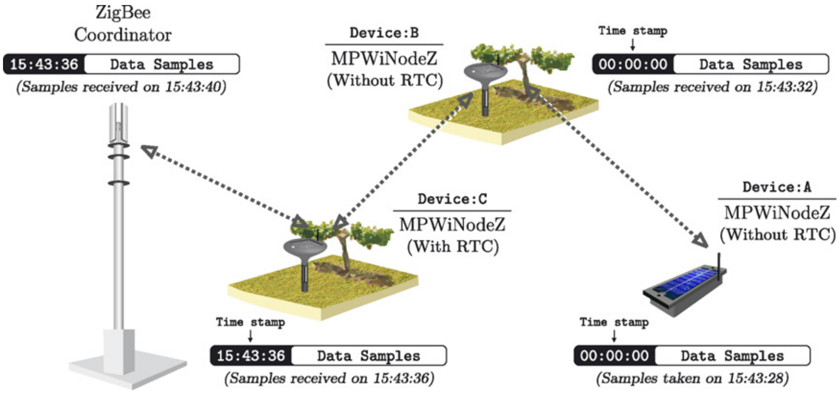

Fig. 10 – Illustration of the insertion of a time stamp in the MPWiNodeZ acquired data.

Fig. 11 – Photograph of an MPWiNodeZ device used in environment monitoring in a vineyard (air and soil temperature, solar radiation and relative humidity in this case).

Fig. 12 shows the first cycle starting from the power-up condition (state 0) until the acknowledge has been received after a successful data transmission (state 5). The power supply current was measured by using a precision 6 1/2 digit multimeter (Keithley model 2000) with data logging capabilities connected to a computer. For this purpose, the maximum number of data points allowed (1000) was used. To fit this power consumption profile into a 1000-point window with sufficient resolution to also describe system operation throughout the entire cycle, the time periods between states were reduced, specifically $T_1 = T_3 = T_5 = 7$ s.

As can be observed from Fig. 12, the total time between State 2 and the end of State 3 is approximately 2 s (T_4), which represents the most power-demanding period. In fact, during this period the MPWiNodeZ device must search an available network and issue a joining request. In order to save a significant amount of battery energy, it is only allowed a one-shot joining process. If it fails, the system will resume $T_{10} + T_3$ later, according to Fig. 8. After this stage, where the network parameters are acquired and saved for later use, the first acquisition task will be triggered T_5 later. For normal operation, the acquisition process will then be repeated every T_9 s. Under the application scope of the MPWiNodeZ device, T_9 may take values of the order of several minutes. With a reasonable value of 10 min, probably even greater, a coarse average current consumption would be given by

$$\langle i \rangle = \frac{I'T' + I_9 T_9}{T' + T_9} \tag{1}$$

where I' corresponds to the average current of the active period (State 4.4 → State 5). Considering $T' \approx T_8 = 2$ s, $T_9 = 600$ s, $I' \sim 40$ mA and the measured sleep current $I_9 = 0.11$ mA, the expression (1) leads to the average value of 243 μA.

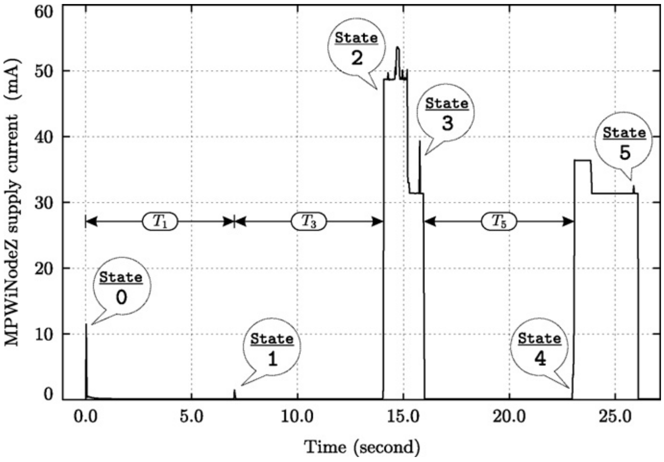

Fig. 12 – Power supply current profile for a normal data cycle.

Fig. 13 illustrates the case when no network is available at that time. As expected, the MPWiNodeZ fails the discovery/joining process and continues to try every $T_{10} + T_3$, assuming that the battery has enough energy.

During this process, and considering a current consumption of 50 mA during T_4 and 110 μA otherwise (sleep times T_{10} and T_3), the average value of current consumption is given by

$$\langle i \rangle = \frac{50T_4 + 0.11T_{10} + 0.11T_3}{T_4 + T_{10} + T_3}\,(\text{mA}) \tag{2}$$

which for the intended application scope with $T_{10} = 120$ s, $T_3 = 120$ s and $T_4 = 2$ s, results in an average current consumption of approximately 522 μA.

During the normal acquisition process, initiated on State 4, the μ-controller checks the battery conditions and loads from

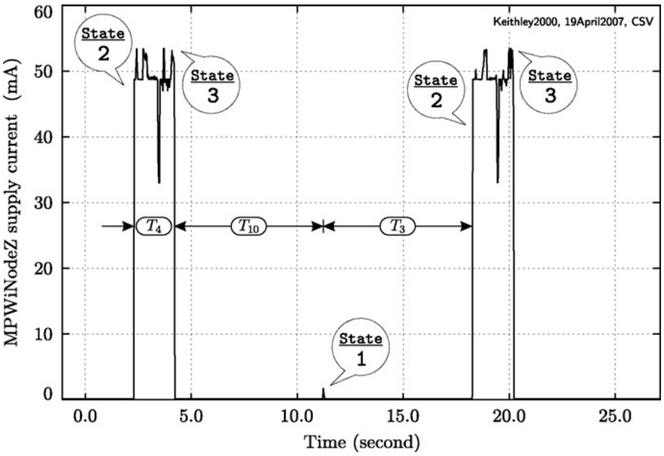

Fig. 13 – Power supply current profile during the discovery and joining network procedures.

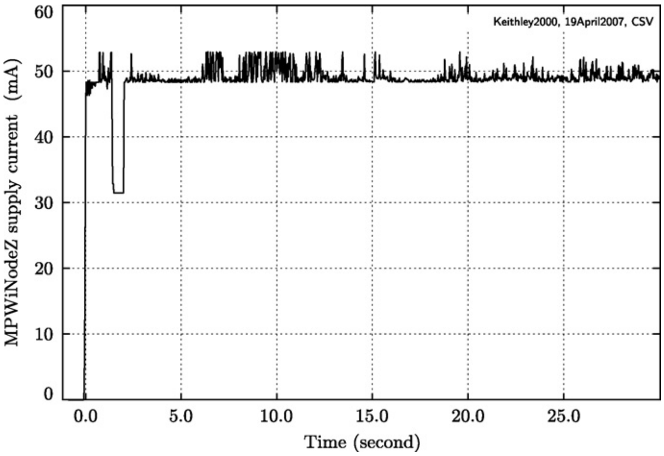

Fig. 15 – Power supply current consumption of the MPWiNodeZ device as a router.

memory the operational rules that specify which channels to be sampled. Fig. 14 shows some waveforms that illustrate this procedure.

The DC–DC converter that supplies the external sensors is turned-on during approximately 100 ms in order to stabilize the voltage output. After this time, external sensors are sampled by the analog-to-digital converter which will enter automatically in a sleep mode after the required conversions. At the same time, if rules apply, the multiplexer is enabled to start averaging the pulse outputs from the power-management block (solar panel in this case). The bottom waveforms of Fig. 14 show this procedure. During this enable period, a pulse train appears at the output of the multiplexer in order to be filtered. After the necessary voltage stabilisation time, the amplifier is powered on, supplying the signal <PULSE_{SP}>, which is amplified by a factor of two, to the μ-controller internal ADC. The time that the multiplexer is enabled can also be observed in Fig. 12 after the State 4. As can be seen, at the end of time T_5, the sensors are turned on and data acquired. After that, the μ-controller enables the multiplexer and goes sleep mode again. After a period of 2 s, it wakes and turns on the amplifier (current consumption has risen from 110 μA to 400 μA). After the acquisition, the MPWiNodeZ performs all computations and send the data samples over the ZigBee network.

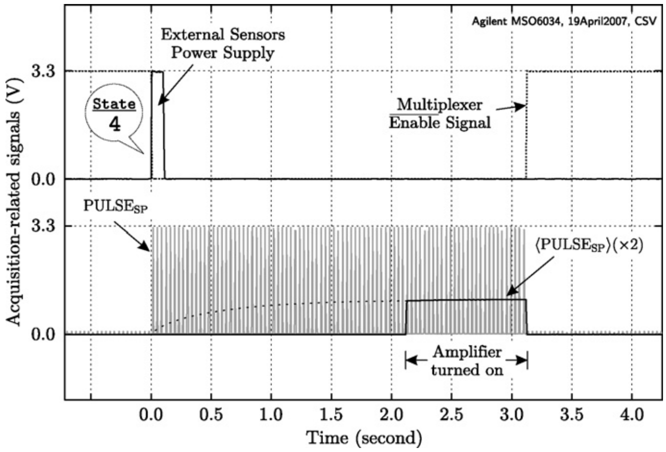

Fig. 14 – Data acquisition-related waveforms.

After the first evaluation phase, one MPWiNodeZ device, still operating as an RFD, was tested as an acquisition device operating under real conditions, as seen in Fig. 11, and sending real-time data over a ZigBee network. The objective of this second evaluation phase was the validation of the described state machine but under operation as a ZigBee network router. For this evaluation scenario, the ZigBee network topology has changed to one coordinator, two network routers (both MPWiNodeZ, one being under evaluation) and an end-device (located in the vineyard). The power supply current consumption of the router device has been traced and is shown in Fig. 15, where it can be seen the router joining process (first 2 s). After this first stage, the MPWiNodeZ operates as expected, routing packets from the end-device to the coordinator and vice-versa. As can be seen, a current consumption of almost 50 mA at all times places significant demands on the power-management system, which may need an energy supplement harvested from the surrounding environment.

Fig. 16 shows the battery voltage profile of the MPWiNodeZ device located in the vineyard. The battery was charged by the low-power solar panel that was also used to measure the solar irradiance. The result of this measurement is

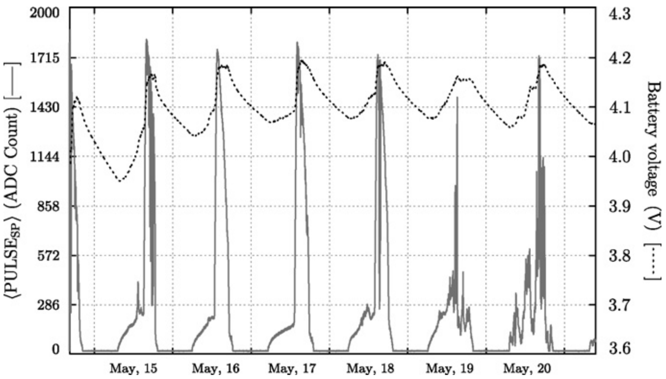

Fig. 16 – Battery voltage profile of the MPWiNodeZ device during a 6-day evaluation.

illustrated as the <PULSE$_{SP}$> value, which is only showed for battery correlation purposes. In this 6-day window, the battery was kept in the charging mode until its voltage reaches almost 4.2 V. When it happens, the software procedure keeps the battery in a float condition providing a trickle charge mechanism. Data were received by the ZigBee coordinator at intervals of 60 s, which we consider the most demanding condition in practice, considering the scope of this MPWiNodeZ application. The battery voltage profile depicted in Fig. 16 has been determined in low–medium solar irradiance values (less than 100 W/m^2), the batteries being charged with this energy source only. As can be seen, even with a data transmission every 60 s, the battery voltage was always above 3.9 V.

6. Final remarks and conclusions

We have shown the feasibility of a ZigBee-based remote sensing network, intended for precision viticulture in the Demarcated Region of Douro. The network nodes are powered by batteries that are recharged with energy harvested from the environment. The power-management aspects have been found to be particularly critical, the main issues being the on–off cycles caused by partially charged batteries, and connectivity/network failures that lead to repeatedly unsuccessful connection attempts. We have designed the nodes to deal correctly with these issues, and tested the correctness of the solutions adopted by testing the nodes under particularly severe conditions.

The testing and deployment of the devices was a two stage process. In the first stage, the devices were tested in the laboratory to validate the solutions that had been implemented, with particular emphasis on the power-management aspects. The power consumption profiles measured during the tests validated the software-based solution, based on a finite state machine. The second and final stage was the deployment of a network of devices in the field (see Fig. 11), a vineyard, with the cooperation of a winegrower. All results obtained so far confirm that the system works as envisaged, and operates reliably. We have concluded that the system nodes are able to sustain themselves based on solar energy alone; in other words, a ZigBee-based sensor network powered by batteries recharged by solar energy alone is feasible, if the networking and power-management issues are handled as proposed. No new hardware or software issues appeared when operating the system in the field.

The system is in principle also able to harvest kinetic energy from wind and water in pipes. However, testing of these harvesting techniques has not been performed, for two reasons: first, these energy sources are more relevant to routers, which need a permanent energy supply, than to network nodes, which are less critical and can shut themselves off if necessary. Second, the performance of the nodes was our main concern and the main purpose of our study. The system was endowed with the possibility of harvesting from both solar and kinetic energy sources in anticipation of future applications, including for example applications in greenhouses. A router placed inside a greenhouse would clearly benefit from harvesting kinetic energy from water in pipes inside the greenhouse itself. The router current consumption of 50 mA would drain fully charged 650 mAh batteries in less than 13 h. The fact that the amount of solar energy is likely to be reduced by the filtering effect of the greenhouse itself provides additional motivation to consider alternate energy sources. The testing of the router and nodes under such circumstances is planned and will be reported in a future work.

Acknowledgments

The authors would like to thank Portugal Telecom Innovation (PT Inovação), which partially supported this work through the project “Wireless Farm”. Electronic components samples for the developed prototypes were kindly supplied by Maxim Integrated Products Inc., CA, USA (MAX856, MAX982, MAX710, MAX4618, and DS1302), Analog Devices, MA, USA (AD7888BRZ), and Coilcraft, IL, USA (Inductors), a fact we gratefully acknowledge.

REFERENCES

Baronti, P., Pillai, P., Chook, V.W., Chessa, S., Gotta, A., Fu, Y.F., 2007. Wireless sensor networks: a survey on the state of the art and the 802.15.4 and ZigBee standards. Comp. Commun. 30, 1655–1695.

Beckwith, R., Teibel, D., Bowen, P., 2004. Report from the field: results from an agricultural wireless sensor network. In: Proceedings of the Local Computer Networks, 2004, 29th Annual IEEE International Conference, November 16–18, pp. 471–478.

Camilli, A., Cugnasca, C.E., Saraiva, A.M., Hirakawa, A.R., Corrêa, P.L.P., 2007. From wireless sensors to field mapping: anatomy of an application for precision agriculture. Comp. Electron. Agric. 58, 25–36.

Delin, K.A., Jackson, S.P., Johnson, D.W., Burleigh, S.C., Woodrow, R.R., McAuley, J.M., Dohm, J.M., Ip, F., Ferré, T.P., Rucker, D.F., Baker, V.R., 2005. Environmental studies with the sensor web: principles and practice. Sensors 5, 103–117.

Ding, H., Zhang, B., Ding, Y., Tao, B., 2007. On a novel low-cost web-based power sensor via the Internet. Sens. Actuators A: Phys. 136, 456–466.

Gomide, R.L., Inamasu, R.Y., Queiroz, D.M., Mantovani, E.C., Santos, W.F., 2001. An automatic data acquisition and control mobile laboratory network for crop production systems data management and spatial variability studies in the brazilian center-west region, Paper number 011046, ASAE Annual Meeting 2001.

Hart, J.K., Martinez, K., 2006. Environmental sensor networks: a revolution in the earth system science? Earth Sci. Rev. 78, 177–191.

IEEE, 2003. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE Standard 802.15.4. The Institute of Electrical and Electronics Engineers Inc., New York, USA.

Jinsheng, S., Ning, W., Liping, L., 2006. Using ZigBee wireless network to transfer water-sludge interface data. In: Proceedings of the 2006 IEEE International Conference on Information Acquisition, Weihai, Shandong, China, August 20–23, pp. 473–477.

Lee, W.S., Burks, T.F., Schueller, J.K., 2002. Silage yield monitoring system. Paper number 021165, ASAE Annual Meeting 2002.

Milenković, A., Otto, C., Jovanov, E., 2006. Wireless sensor networks for personal health monitoring: issues and an implementation. Comp. Commun. 29, 2521–2533.

Morais, R., Boaventura, J., Cordeiro, M., Salgado, P., Serôdio, P., Couto, C., 1996. Solar data acquisition wireless network for agricultural applications. In: Proceedings of the 19th Convention of Electrical and Electronics Engineers, Israel, November 5–6, pp. 527–530.

Oostdyk, R.L., Mata, C.T., Perotti, J.M., 2006. A Kennedy Space Center implementation of IEEE 1451 networked smart sensors and lessons learned. In: Proceedings of the Aerospace Conference, IEEE, March 4–11, pp. 0–20.

Raghunathan, V., Ganeriwal, S., Srivastana, M., 2006. Emerging techniques for long lived wireless sensor networks. IEEE Commun. Mag. 44 (4), 108–114.

Seelan, S.K., Laguette, S., Casady, G.M., Seielstad, G.A., 2003. Remote sensing applications for precision agriculture: a learning community approach. Remote Sens. Environ. 88, 157–169.

Valente, A., Morais, R., Tuli, A., Hopmans, J.W., Kluitenberg, G.J., 2006. Multi-functional probe for small-scale simultaneous measurement of soil thermal properties, water content and electrical condutivity. Sens. Actuators A: Phys. 132 (1), 70–77.

Wang, N., Zhang, N., Wang, M., 2006. Wireless sensors in agriculture and food industry—recent development and future perspective. Comp. Electron. Agric. 50 (1), 1–14.

Raul Morais dos Santos graduated in Electrical Engineering from the University of Trás-os-Montes and Alto Douro (UTAD), Portugal in 1993. He obtained the M.Sc. degree in Industrial Electronics in 1998 from the University of Minho, Portugal and the Ph.D. degree in Microelectronics in 2004 from the UTAD. Presently, he is an Assistant Professor in the Department of Electrical Engineering, UTAD. He is also a researcher in the Signal Processing and Biotelemetry group at the Center of Technological Studies for Environment and Life (CETAV) of UTAD, and he is involved in the development of instrumentation solutions and mixed-signal sensing interfaces for agricultural applications. He is also leading the CETAV effort of implementing an agricultural remote sensing network in the Demarcated Region of Douro.

Miguel Alves Fernandes graduated in Electrical Engineering from the University of Trás-os-Montes e Alto Douro (UTAD), Portugal in 2005. He is pursuing its Ph.D. degree in Electrical Engineering, and working on the wireless farm concept in precision viticulture environments.

Samuel R.G. Matos graduated in Electrical Engineering from the University of Trás-os-Montes e Alto Douro (UTAD), Portugal, in 2005. He is pursuing its Ph.D. degree in Electrical Engineering and pursuing work in highly flexible smart acquisition devices.

Carlos Manuel Alves Serôdio received the M.Sc. and Ph.D. degree from the University of Trás-os-Montes e Alto Douro (UTAD), Portugal, in 1996 and 2002, respectively. Presently, he is an Assistant Professor in the Department of Electrical Engineering, UTAD, Portugal. He has been Director of the Electronics and Electrical Engineering course. He is the Legal Main Contact and Career Connection Contact at Local CISCO Academy at UTAD. He is also a researcher in the Telemetry and Communication group at the Center of Technological Studies for Environment and Life (CETAV) of UTAD, and he is involved in the development of systems and solutions for Mobile and Wireless Communications and Dynamic and Distributed Systems Java-enabled.

Paulo J.S.G. Ferreira is Full Professor at the Departamento de Electrónica, Telecomunicações e Informática of the University of Aveiro, Portugal. He was an Associate Editor of the *IEEE Transactions on Signal Processing*, and is currently a member of the editorial board of the *Journal of Applied Functional Analysis* and an Editor-in-Chief of *Sampling Theory in Signal and Image Processing*. He co-edited with John J. Benedetto the book *Modern Sampling Theory: Mathematics and Applications*. His current research interests include sensors and coding, bioinformatics and symbolic signals, as well as sampling and signal acquisition and reconstruction.

Manuel J. Cabral S. Reis received the Ph.D. degree in Electrical Engineering and the M.Sc. degree in Electronics and Telecommunications from the University of Aveiro, Portugal. Currently he is Assistant Professor in the Department of Engineering of the University of Trás-os-Montes e Alto Douro (UTAD), Portugal. He is also a researcher at the Center of Technological Studies for Environment and Life (CETAV) of UTAD, where he is the director of Signal Processing and Biotelemetry group. His research interests are in the area of signal processing, and include modelling and approximation, and problems such as sampling, interpolation, and signal reconstruction.