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An autonomous intelligent gateway infrastructure for in-field processing in precision viticulture

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ABSTRACT

Wireless sensor networks have found multiple applications in precision viticulture. Despite the steady progress in sensing devices and wireless technologies, some of the crucial items needed to improve the usability and scalability of the networks, such as gateway infrastructures and in-field processing, have been comparatively neglected. This paper describes the hardware, communication capabilities and software architecture of an intelligent autonomous gateway, designed to provide the necessary middleware between locally deployed sensor networks and a remote location within the whole-farm concept. This solar-powered infrastructure, denoted by iPAGAT (Intelligent Precision Agriculture Gateway), runs an aggregation engine that fills a local database with environmental data gathered by a locally deployed ZigBee wireless sensor network. Aggregated data are then retrieved by external queries over the built-in data integration system. In addition, embedded communication capabilities, including Bluetooth, IEEE 802.11 and GPRS, allow local and remote users to access both gateway and remote data, as well as the Internet, and run site-specific management tools using authenticated smartphones. Field experiments provide convincing evidence that iPAGAT represents an important step forward in the development of distributed service-oriented information systems for precision viticulture applications.

1. Introduction

Precision agriculture (PA) and precision viticulture (PV) involve using electronic, communication and information technologies to collect large amounts of data in the field to use in site-specific crop management (Stafford, 2000). Wireless sensors are considered the best technology to gather the massive amounts of data needed, for example, to understand production variability (Camilli et al., 2007) or estimate growth profiles (Moreenthaler et al., 2003). Arranged to form widespread *ad hoc* networks, known as wireless sensor networks (WSN), they have been used to assist in spatial data collection, precision irrigation, variable-rate technology and in supplying data to farmers (Lamb and Bramley, 2001; Wang et al., 2006). However, these technologies are still far from being firmly established in agricultural practice and farming enterprises (Kitchen, 2007).

The volume and nature of the data introduce a significant challenge in the development of WSN in PA. Massive amounts of raw data do not necessarily yield proportional amounts of information. There are obvious difficulties in interpreting the data involved in order to reach a better understanding of the causes of variability and in proposing sound strategies for field variability management (Murakami et al., 2007; Rundel et al., 2009; Bramley, 2009). The nature of the data also brings difficulties: the data are heterogeneous and the management of heterogeneous data sources poses specific problems (Plant, 2001). The task of getting meaningful information from many disparate sensors is not trivial (Ibrahim et al., 2005).

Energy and networking issues need also to be considered. Typically, a large and remote agricultural area has to be covered with small data acquisition devices, which must harvest energy to run (Morais et al., 2008b). Each device faces severe power constraints, and the coverage of large areas may only be possible if several levels of internetworking are combined to achieve a higher level of network performance and scalability.

To better manage the data and address the networking and scalability issues we propose to carry data aggregation and data

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integration in the field, close to the WSN. This implies the creation of an intermediate layer of aggregation nodes that manage the sensor networks and perform local data integration and supervision functions.

The goal of this paper is to describe an intelligent gateway (iPAGAT) that implements this intermediate layer and the underlying data processing functions. The gateway provides capabilities that we consider critical to the success of PV and PA in general: hierarchical networking, remote management, *in situ* interactions, Internet access and site-specific management tools. It also helps to convert the raw bits into useful information for the farmer and to distribute the processing load. The intermediate layer fits very well to the demands of power-constrained wireless sensors and provides a link between the sensors and the central office or decision center: a link that we regard as critical but that has largely been missing.

This paper is organized as follows. The next section discusses the motivation in more detail and puts the paper in perspective with respect to the state-of-the-art, focusing on the hierarchical management of agricultural zones, the use of WSN in distributed monitoring of the environment and in-field data processing topics. The material and methods section describes the iPAGAT gateway in detail: its hardware and features, the communication capabilities and the software architecture. The experiments and results section gives a detailed account of the experiments performed to evaluate the gateway as well as some results achieved with the current implementation. The paper closes with the conclusion and discussion section, which summarises our findings and highlights the main contributions of this research.

2. Motivation and background

2.1. WSN in distributed monitoring of the environment

The advantages of using WSN technologies to assist PA/PV practices (Wang et al., 2006) are far reaching and motivating. Unfortunately, the effective and general deployment of wireless sensing devices remains constrained by energy requirements and networking issues (Thomas et al., 2006; Raghunathan et al., 2006). Because of this, practical implementations often use some sort of sink node or base station (usually free of energy restrictions) to collect and relay data from field WSNs to upper data processing layers, typically relegated to a remote location.

Smart irrigation systems are a good example of this. They are among the most frequently used WSN applications. The sensors are used to assess the hydrological status of the soil and control the site-specific irrigation process. For instance, Vellidis et al. (2008) present a low-cost sensor array that is used to assess soil moisture contents in a cotton crop and transmit sensor data wirelessly to a centralised receiver, which works as the sink node. Kim et al. (2008) describe an irrigation system that uses wireless devices to acquire soil humidity data samples and send them to an in-field base station, which performs the decision-making required for an efficient use of the irrigation water.

The use of WSN technology to study the variability in vineyards is reported by Beckwith et al. (2004). They describe a 65-node, 8-hop depth network deployed across a 2-acre vineyard that is used to acquire and transmit temperature data to a base station within the managed zone, for the purpose of studying frost pocket, cold patterns and heat unit accumulation differences and their effect on *Vitis vinifera* grapes.

The NAV system (Matese et al., 2009) consists of a base agrometeorological station (Master Unit, placed in a representative site) and a series of peripheral wireless nodes (Slave Units), up to a maximum of 20, located in the vineyard. It adopts a proprietary wireless technology that uses the ISM 433 MHz band and a proprietary half-duplex data transfer protocol for communication with the Slave Units. In this implementation, the Master Unit stores all of the Slave Units data and is able to forward them to a remote central server, using a GSM/GPRS device.

Mainwaring et al. (2002), Suri et al. (2006) and Rundel et al. (2009) examine the requirements of environmental WSN used to monitor wildlife habitats. In addition to hardware design and energy issues, their research also focuses on the remaining general key issues that should be considered for the effective deployment of scalable WSNs: hierarchical networking, remote management, *in situ* interactions and Internet access, among other aspects.

The concept of Field Server is explored by Fukatsu and Hirafuji (2005), who introduced a sensor-node equipped with a web server and a wireless LAN (IEEE 802.11b/g) to create a remote field monitoring system. Each Field Server is a standalone device that provides Internet access with hotspot capabilities. This solution can provide ubiquitous networking in PA/PV environments but the devices need to be permanently connected to their neighbourhoods, adding to the energy needs.

2.2. Hierarchical management of agricultural zones

Proprietary solutions regarding data communications protocols can always be effectively employed but are often the rule in the case of emerging and/or experimental technologies. Industry standards have important and well-known advantages and are usually associated with more mature stages of development. Wireless personal area networks (WPAN) are no exceptions to this. The lack of standardisation in WPAN lead the Institute of Electrical and Electronic Engineers (IEEE) to design the IEEE 802.15.4 WPAN family of standards, intended for low-power, low bandwidth sensor applications (IEEE, 2006; Baronti et al., 2007). IEEE 802.15.4 enables the creation of complex *ad hoc* networks, allowing ultra-low power devices, with very short wake-up times at very low cost. This standard assumes that the payload transmitted is short and that transmissions occur at a low duty-cycle. These characteristics are adequate for applications that require a very long battery life or even the combination of energy harvesting techniques with rechargeable batteries (Rundel et al., 2009; Morais et al., 2008a,b). Within an IEEE 802.15.4 WPAN, the network is created and managed by a unique network coordinator, which acts as a sink node to all network nodes. This makes the standard suitable for clustered and mesh WSN architectures.

From the management zone perspective, López et al. (2009) present a field implementation of a horticultural crop monitoring network that uses gateways to relay data from in-field WSN back to a base station located at the farm offices. Temperature, relative humidity, electrical conductivity, soil moisture and salinity are among the parameters that are measured by sensing nodes that exchange data using IEEE 802.15.4 low-power links.

From the energy and networking requirements viewpoint, the coverage of large and remote agricultural areas with small data acquisition devices that need to harvest energy to run (Morais et al., 2008b) requires the combination of several levels of internetworking for optimum networking performance and scalability. To achieve this, data aggregation and data integration should be accomplished in the field, close to the sensor network. The resulting intermediate layer of aggregation nodes would manage the sensor network, performing local data integration and supervision. Multiple management zones could be easily identified and managed.

The advantages of an intermediate layer between the data acquisition layer and the upper level processing and decision support systems, which many authors regard as middleware (Yu et al., 2003; Heinzelman et al., 2004; Curino et al., 2005; Hadim and

Mohamed, 2006), become clear. However, the need to render, process and interpret the data that arises from intensive field data acquisition (Kitchen, 2007) makes efficient system integration a critical goal.

2.3. In-field data processing and services

The heterogeneity of the sensor nodes or data acquisition devices poses a challenge that needs to be addressed in order to give a satisfactory solution to the PV problem. The heterogeneity makes the extraction and aggregation problems more difficult and broadens the gap between the acquisition of the data and their availability at the processing layer. On the other hand, some authors (Govindan et al., 2002; Hu and Kumar, 2006; Choochaisri and Intanagonwiwat, 2008) have considered sensor networks as a distributed database, which suggests the creation of query mechanisms for accessing summarised information related to the managed area, as well as lists of sensors and sensor attributes (Johannes et al., 2001).

The deployment of in-field gateways and the associated intermediate layer would help to meet the networking and scalability demands, allow data aggregation and integration where it makes more sense – in the field, in the vicinity of the sensor network – and would ease the implementation of in-field data processing and services.

In-field gateways may act as service providers to local users through the use of common wireless technologies, such as Bluetooth (Garg, 2007) or IEEE 802.11 (Fukatsu and Hirafuji, 2005). Site-specific management tools can then access all gateway data by using a smartphone after an authentication process. Examples of such applications are described by Cunha et al. (2010), who use visual tags to automatically associate a field location to its relevant database tables or records, and to access contextual information or services, useful in PV practices. Fang and He (2008) also emphasise the importance of in-field data processing and management infrastructures. They describe a field information collection, control and management system targeted at PA practices and which is expected to serve as a foundation for the development of field data collection equipment.

Our goal when designing the iPAGAT was to meet the multiple requirements discussed throughout this section. The gateway, described in the next section, allows hierarchical networking and remote management, but it also provides Internet access and supports *in situ* interactions and site-specific management tools.

3. Materials and methods

In this section we describe the implementation of iPAGAT, an intelligent and autonomous gateway for in-field processing that we regard as a crucial element of our PV system. We describe first its relation with the rest of our PV system, then its overall architecture, and finally the hardware and software implementation details.

3.1. Background and overview of the system

The iPAGAT gateway is part of a long-term effort to establish PV in the hillside vineyards of the Douro Demarcated Region (DDR) in Northeast Portugal. The soil of the region is mainly based on complex schist, which makes the assessment of the hydrological status difficult. The vineyards have unique characteristics. The topographic aspects, erosion control, vertical planting, limited water availability, and wide temperature span across all day and year dictate the use of distributed field monitoring and information processing for both operation and performance assessment, in the context of zonal vineyard management.

Fig. 1 illustrates the scenario and identifies all the relevant management levels. The bottom layer (L1) embraces all data gathering procedures and relies on WSN technology to collect environmental data within vineyards grouped as a management zone. Layer 2 (L2) devices coordinate the WSN and perform local processing tasks, such as data aggregation. They can also act as an in-field local access point (AP) to site-specific management applications. L2 entities, as gateways to the managed zones, are connected to a Layer 3 (L3) entity which is responsible for farm management in a whole-farm basis concept. Higher layers (L4 and L5) are related to farmer associations and country policies and will not be discussed in this article.

In this scenario, three levels of communication networking can coexist: WSN links between gateways and sensor nodes (L2 ↔ L1 connections), Bluetooth and/or IEEE 802.11 links between gateways and local user mobile devices (L2 ↔ smartphone

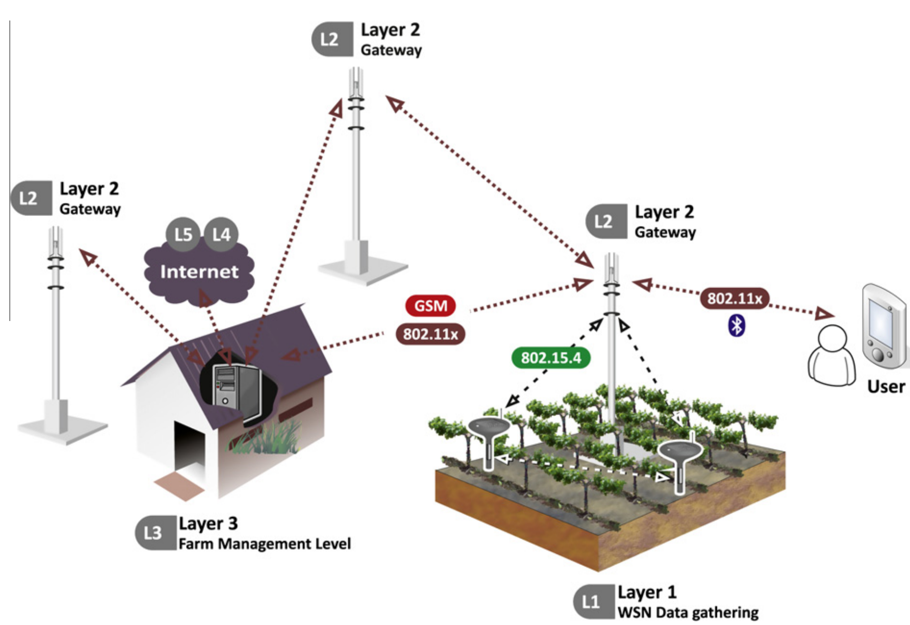

Fig. 1. Distinctive management levels that can be identified in the envisioned PA/PV distributed monitoring environment.

connections), and long-range GSM/GPRS and/or IEEE 802.11 links between gateways and the farm management level (L2 ↔ L3 connections).

The small stationary data acquisition devices denoted by MPW-iNodeZ (Morais et al., 2008a) are an important component of the scenario illustrated in Fig. 1. They are deployed across a specified management zone following a mesh network topology, according to the ZigBee standard. This network has its coordinator operating at the gateway infrastructure of the managed area. Besides WSN management, the network coordinator also operates as a sink node for the gathered data, filling up the gateway database, where data aggregation is performed. The gateway (L2 layer) is also responsible for making data available locally and/or to upper layers, through the use of web-services.

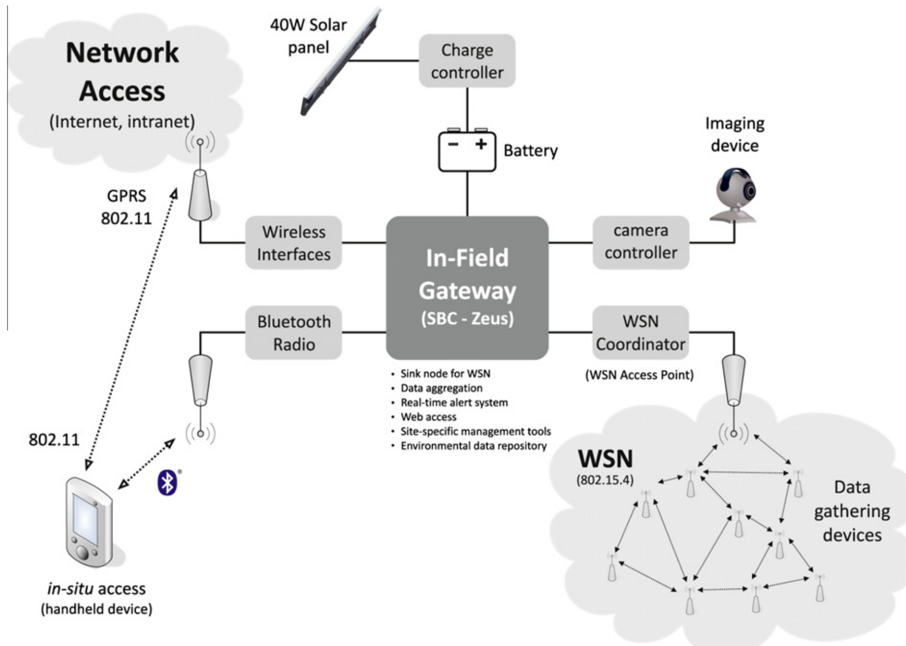

Fig. 2. The gateway functional overview. It uses a single-board computer as the processing core and a set of peripherals enabling WSN coordination, connectivity support for in-field access, imaging devices and an IP-based network infrastructure used to remotely access and manage the gateway and its information.

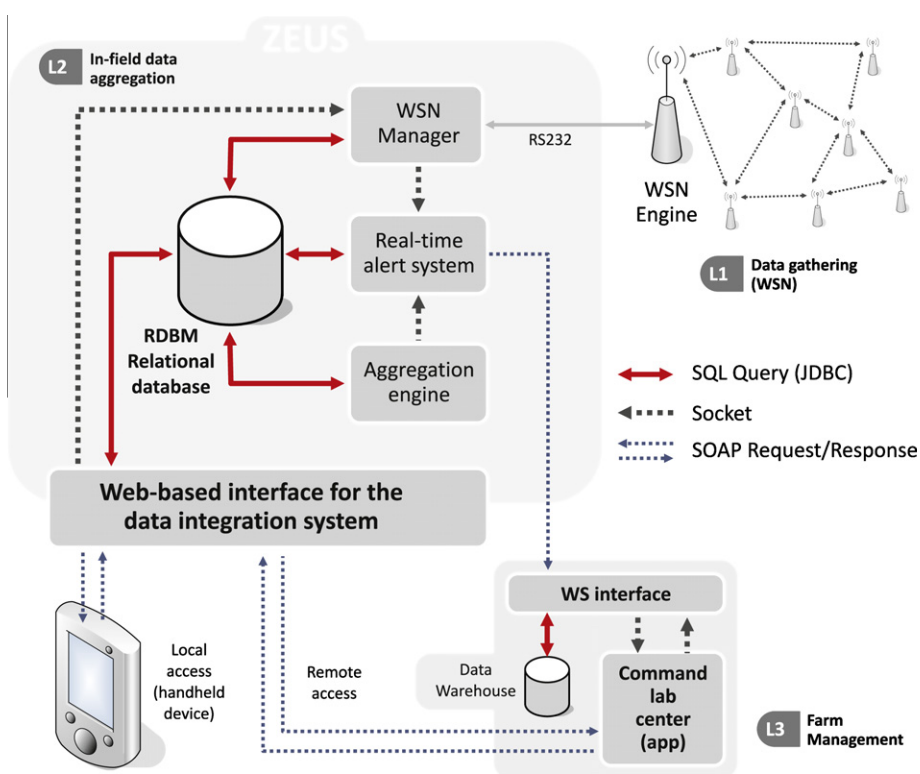

Fig. 3. A functional overview of the software architecture of iPAGAT.

Having provided the necessary background information, we may now describe the gateway architecture in detail.

3.2. Gateway architecture

The gateway architecture is illustrated in Fig. 2 (system) and Fig. 3 (software). This section gives only a high-level, block-oriented overview of the system. Details about each block will be given in the following sections.

The iPAGAT gateway is powered by means of a solar panel combined with a rechargeable battery, under the control of a voltage supervision system. The inter-network connection capabilities of iPAGAT gateway are shown in Fig. 2: Bluetooth and IEEE 802.11 technologies are needed to allow authenticated smartphones to access information in the field. In addition to this range of connectivity solutions, the iPAGAT also supports real-time video streaming captured by a 2-axis positioned web camera, useful for image-based applications, such as remote surveillance.

As shown in Fig. 3, the software architecture of iPAGAT is built around a relational database management system (RDBM), which provides the main repository for the data gathered from the WSN as well as for the WSN operating rules, and three Java applications: the WSN manager, the Aggregation Engine and a Real-Time Alert System, RTAS.

The WSN manager links the WSN, which produces the data, to the RDBM, where the data are stored or aggregated. It performs a number of auxiliary tasks, including network creation, management, and device configuration. Its main task, however, is to collect the data produced by the WSN acquisition devices and signal to the RTAS whenever new data have become available.

WSN are notorious producers of massive amounts of heterogeneous information. The data aggregation engine takes the data produced by the WSN and summarises them by aggregation. It periodically goes over the data and updates their mean, maximum and minimum values, storing the updated results back in the data base.

The RTAS reacts to both real-time sensor readings stored in the data base and the data produced by the aggregation engine. Its purpose is to check if the sensor readings are within certain (programmable) limits. If the limits are exceeded, the RTAS sends an alert to a remote user using a SOAP (Simple Object Access Protocol) request. As discussed elsewhere, this can be used to detect combinations of climacteric factors that favour the occurrence of diseases or plagues, and trigger alarms if and when they are detected.

3.3. Hardware description

The iPAGAT infrastructure is preferably a fixed structure comprising a single-board computer (SBC), a IEEE 802.15.4 WSN coordinator, a long range IP-based GSM/GPRS modem and a IEEE 802.11 AP (Access Point), all powered by a rechargeable battery, which is charged using a solar-panel.

As we have seen in Fig. 2 iPAGAT supports Bluetooth and IEEE 802.11 technologies, as well as real-time video streaming captured by a 2-axis positioned web camera, useful for applications such as remote surveillance. It also has to meet the computational processing needs required by local aggregation and data integration tasks.

To comply with these demands, the iPAGAT was built around the SBC Zeus (Eurotech Ltd., UK). This device, illustrated in Fig. 4, is an ultra low power EPIC (Embedded Platform for Industrial Computing, 165 mm × 115 mm) single board computer based on Marvell's 520 MHz PXA270 XScale® processor. The PXA270 is an implementation of the ARM compliant Intel XScale microarchitecture combined with a comprehensive set of integrated peripherals including an USB host/client controller, interrupt controller and multiple serial ports.

The Zeus includes a site for a variety of wireless modems and is designed to create cost effective solutions in asset monitoring and network solutions. To this effect, Eurotech Ltd. has released a GSM/GPRS, iDEN, CDMA modem, and GPS, using a low profile add-on module. Other features include an onboard DC/DC power supply unit, two Ethernet ports, two USB host ports and seven serial ports, which are used to connect several external devices.

Besides its 256 MB of SDRAM and 64 MB of flash memory, a 8-GB USB memory pen is used as an external disk for the operating system and filesystem. The Zeus runs a Debian Linux Operating System (OS), with power-saving applications in order to enable/disable peripherals, to support all the software needed to the embedded data aggregation and integration systems. To this effect, Zeus becomes a fully functional server with SSH, FTP, web server (Apache 2), MySQL Server, PHP, IPTables, Java and Tomcat support.

The energy to power Zeus is harvested from the sun by means of a 40 W solar panel (KC40, Kyocera, Japan) combined with a 25 Ah rechargeable dryfit battery (A512/25G5, Sonnenschein, Germany) and a voltage regulator (Solsum 6.6C, Steca, Germany). To prevent undervoltage damage, we designed a voltage supervisor sub-system that deactivates the Zeus device when the battery voltage falls below a predefined voltage level, the current trip point being 11.5 V. When an undervoltage condition is detected, the voltage supervision sub-system issues a command through an available RS232 port, halting the system and causing a soft shutdown. When the battery charge reaches a safe level (terminal voltage of about 13.0 V), the supervision sub-system reconnects Zeus power, which makes it boot normally.

3.4. Connectivity support

One of the major goals of the iPAGAT infrastructure was to provide an intermediate, in-field level of inter-networking through any available wireless standard. To this effect, three categories of wireless communications are provided. First, a standard wireless protocol to support L1 layer data gathering functions, as the ones provided by any compliant WSN. Second, a layer provided by a local wireless network, created through the use of standard wireless protocol, that may be used to establish a connection with a smartphone. Finally, a third layer that uses a long-range IP-based protocol to provide Internet and Intranet connections to iPAGAT.

In order to support a WSN that builds upon IEEE 802.15.4/ZigBee standard, such as those presented in Morais et al., 2008a, an IEEE 802.15.4 network coordinator is required. The physical implementation of the IEEE 802.15.4/ZigBee WSN coordinator was accomplished by using an USB Dongle (IA OEM-DAUB1 2400, Inte-

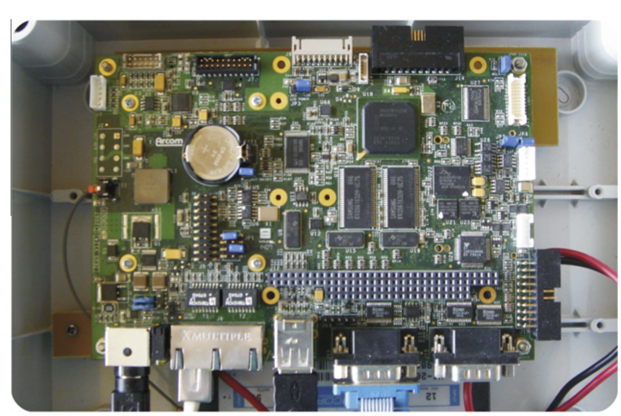

Fig. 4. Photograph of the gateway hardware (ZEUS-M128-F32-001-R6 from Eurotech Ltd., UK), illustrating the SBC platform that supports all processing tasks and peripheral devices.

gration, UK). This IEEE 802.15.4 interface can be quickly and easily connected to the Zeus through the USB 1.1 interface and provides a simple method of integrating IEEE 802.15.4/ZigBee into L2 gateways. The dongle is available with a choice of two driver options: the IEEE 802.15.4 drivers provide direct access to the IEEE 802.15.4 MAC interface and the ZigBee drivers allow the dongle to operate within a ZigBee network and expose the AF/ZDO Application Interfaces. With such functionality, the development of an effective WSN manager becomes straightforward.

Smartphones of authenticated users can access the iPAGAT system through a WPAN created with Bluetooth technology or/and by means of a WLAN using IEEE 802.11 technology. To this effect, the iPAGAT is equipped with a Bluetooth dongle (CBT200U2A, Conceptronic, The Netherlands). This provides a simple interface to access field information, to configure iPAGAT settings and to perform other data management operations. iPAGAT also makes available a WLAN using an IEEE 802.11 AP (Open-Mesh, Wireless Mesh Router, OMIP Model), connected to Zeus through an Ethernet cable.

To accomplish the goal of providing communications support between iPAGAT and the higher management level (farm management level, L3 in Fig. 1), each iPAGAT is equipped with an add-on GSM/GPRS wireless modem board and an AP, with mesh network support, enabling an ubiquitous networking environment. With this AP, each iPAGAT can operate in bridge/repeater, access point and client modes, and act as a data relay point.

3.5. Software architecture

The block-level view of the software architecture of iPAGAT has already been briefly described, based on Fig. 3. The figure shows that iPAGAT has several communication interfaces, accessible through a web-based interface. These are needed to exchange data with local handheld devices and remote L3 farm management applications, which includes a global data warehouse. The iPAGAT gateway uses an external WSN manager to coordinate a IEEE 802.15.4 compliant network, composed by multichannel acquisition devices that are deployed across a management zone.

We will now discuss the main software blocks of iPAGAT in some more detail. These are the RDBM and three Java applications: the WSN manager, the Aggregation Engine and a Real-Time Alert System, RTAS.

3.5.1. The relational database management system

The RDBM is the main data repository of iPAGAT and is built around a MySQL RDBM. Fig. 5 depicts the relational diagram of the RDBM, composed by 10 tables.

The main table is called `zeusdb.nodes` and it has an entry for each acquisition device in the network. The primary key of this table provides the most convenient way of referring to any specific network device. Each device is also classified according to a user-specific management zone. This is accomplished by using the table `zeusdb.zone`, in which the field `Coordinates` stores a relevant location within the zone. Since each acquisition device may have more than one sensor, the database has the additional table `zeusdb.nodesensors` which stores the information about each sensor. Rules of operation are described through table `zeusdb.rules`, which contains trip point values that are used by the RTAS.

Microclimacteric data, acquired by any compliant IEEE 802.15.4 network device, is gathered by the WSN manager and stored in the table `zeusdb.sensordata` for a 7-day period in a FIFO basis. The fields `Node` and `Channel` identify and classify each data source by utilisation purpose and by management zone. Summarised information (aggregation data) regarding all sensor data is produced by the Java aggregation engine, which runs periodically and fills up the table `zeusdb.aggdata`. The content can then be uploaded to a global data warehouse, through queries over the data integration interface. A third Java application, the core of the alert system, inspects the tables, compares their data with threshold values, and depending on the circumstances produces an alarm or a generic event. These applications are described hereafter.

3.5.2. WSN manager and WSN engine

The WSN manager is a Java application running on iPAGAT that basically controls an external IEEE 802.15.4 network coordinator (WSN engine) through a UART physical connection. Besides network creation and management operations, the WSN manager is responsible for data operations over the deployed WSN, such as device configuration and sensor data exchange.

When new data reaches the WSN engine, as a result of an individual measurement taken on an acquisition device, it is converted to engineering units using the parametrisation defined in `zeusdb.units` and `zeusdb.sensortype` tables and the result is stored as a new entry in the `zeusdb.sensordata` table. Each entry in this table is composed of the source identification, network node identification, acquisition channel related to each node, measurement data and associated time stamp, enabling full characterisation of each data sample. After data insertion in `zeusdb.sensordata`, the RTAS is signalled (through an internal data socket) with the new data available.

3.5.3. The data aggregation engine

As mentioned before, each WSN acquisition device can be regarded as an independent data source that generates records with several fields. When considering a routing protocol to communicate with nodes that are spatially distant, such as the standard IEEE 802.15.4 (IEEE, 2006), or in the case of nodes with limited computation, energy and storage capabilities, several issues arise, such as network traffic overload. WSN may generate a huge amount of data coming from a multitude of heterogeneous data sources. The traffic is usually centralised or forwarded to the sink node. These large data sets cannot be transmitted regularly and efficiently to higher-level processing stages without being aggregated. Aggregation may also be useful to increase the range of knowledge, level of accuracy and to create data redundancy to compensate for software or hardware failures in WSN nodes (Ibrahim et al., 2005; Akkaya et al., 2008; Tubaishat et al., 2003). Under this point of view, every sensor reading that reaches the WSN manager is aggregated to compute a summarised result available through the web-based integration system.

According to Akkaya et al. (2008), data aggregation is the process of combining multiple data packets into one by looking at their contents. In iPAGAT, the data aggregation engine is a Java application that makes periodic data iterations, with period determined by the field `zeusdb.AggDataCycleTime` of the `zeusdb.config` table. The first task executed by this application is to build the query for getting the data of the whole day for each channel of an acquisition device. It then executes the query and saves the result. Next, it calculates the mean, the maximum and the minimum values and executes an `UPDATE` statement with the calculated values and the last set of values. If there is no entry to update, it executes an `INSERT` statement. At the end of each aggregation cycle, the aggregation engine signals the RTAS with new data (from `zeusdb.aggdata` tables).

3.5.4. Real-time alert system

The RTAS is a Java application that, as seen in Fig. 3, runs on top of the RDBM system and reacts to the real-time sensor readings and the summarised information that results from the data aggregation process. It illustrates the benefits of local processing and decision.

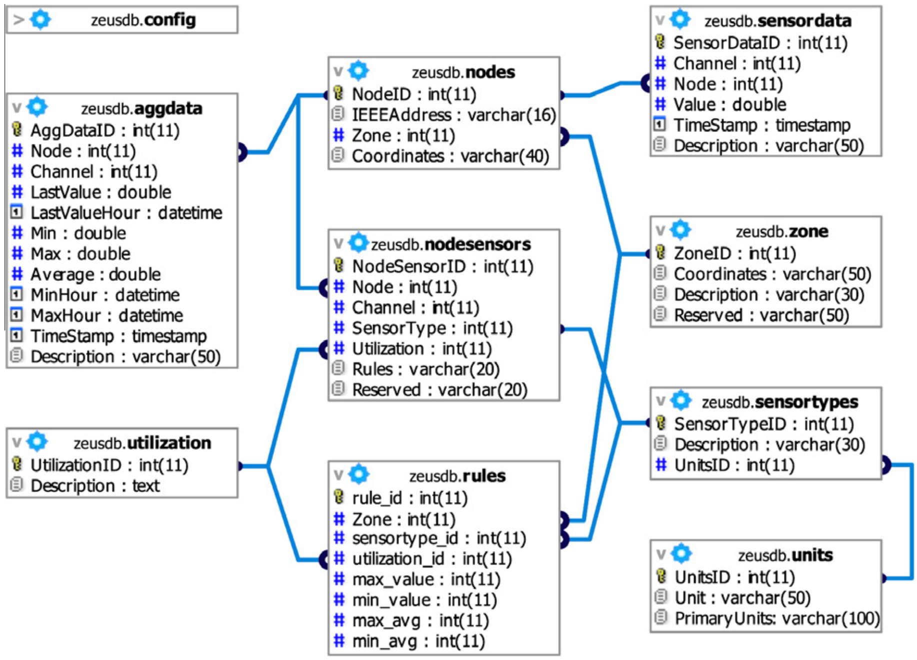

Fig. 5. The entity-relational database structure as a part of the iPAGAT software architecture.

It has a socket-based interface with both the WSN manager and aggregation engine and a SOAP web services based approach. SOAP provides a uniform and reliable mechanism for data exchange over TCP/IP links, and eases the interaction with mobile devices (such as smartphones or cellphones) and the connection with remote management applications.

The purpose of the RTAS engine is to check the data from both the WSN manager and the aggregation engine to verify if sensor readings stored in the tables `zeusdb.aggdata` and `zeusdb.sensordata` are within the limits defined by the fields `min_value` and `max_value` of the table `zeusdb.rules`. If the limits are exceeded, the RTAS sends an automatic alert to a remote user using a SOAP request. Functional flowchart is depicted in Fig. 6. The alerting system can also be used to signal the existence of conditions favourable to the occurrence of diseases or plagues based on the combination of certain climacteric factors. For example, if the soil moisture in a certain region reaches values below a minimum defined value, an automatic alert is issued in order to turn-on an irrigation valve. Listing 1 illustrates the conceptual definition of a RTAS rule while Listing 2 gives an example.

3.5.5. The data integration interface

All the mentioned software components have been built with the goal of collecting and aggregating data from heterogeneous data sources such as those provided by WSN.

The data integration system is at the interface with the iPAGAT and it basically bridges two different realities: one responsible for collecting and making data available, and another that makes intensive use of such data without the need to know how it is generated, processed and returned. The data integration system was designed with the goal of providing a high-level access to sensor data stored in a in-field WSN gateway.

The implementation of iPAGAT data integration system interface follows a WS approach, and provides the necessary query mechanism for retrieving gateway data. To improve query processing efficiency, there are basically two types of queries corresponding to the two types of data and tables: raw data and aggregated data.

The first query type is related to the raw data that is available in each gateway RDBM system and follows the on-demand approach (i.e., extracting data from the `zeusdb.sensordata` table only when the query is posed). This query enables the retrieval of individual sensor data. It is buffered in a 7-days time period window before being discarded. The command center or any authenticated user can use this mechanism whenever needed.

The second type of query is related to the gateway summarised information, stored in the iPAGAT `zeusdb.aggdata` table. The result of each aggregated engine cycle is stored in the appropriate table for a 7-day time period window. Raw data and aggregated data tables are continuously updated by the RDBM system by inserting new data and discarding old one. While raw data is permanently discarded, summarised information can be transferred to a data warehouse by issuing an appropriate query. Summarised data older than this 7-day period must be requested directly to the data warehouse. By using this approach, global query processing is optimised, gateway query processing is made more efficient and data exchange between iPAGAT and the data warehouse can be relegated to periods of low network activity.

The web-based data integration interface defines a set of WS containing all operations that are needed to handle gateway data. As an example, the operation `getSensorData_by` is shown in Listing 3. As observed, the user provides high-level parameters as `Zone`, `Utilisation`, `SensorType`, etc., in order to get/retrieve data, instead of using low-level ones such as `NodeID`, `Channel`, etc.

4 Experiments and results

An experiment was conducted on vineyards at the UTAD Agricultural Research Centre, Vila Real, Portugal, starting in the Spring of 2008, with three main objectives: (1) the study of hi-power ZigBee wireless devices and their impact on the well established MPWiNodeZ data acquisition platform (Morais et al., 2008b); (2) the evaluation of iPAGAT hardware and power management techniques, based on a solar panel/dry fit battery set-up; (3) the evaluation of the built-in data aggregation engine and the data

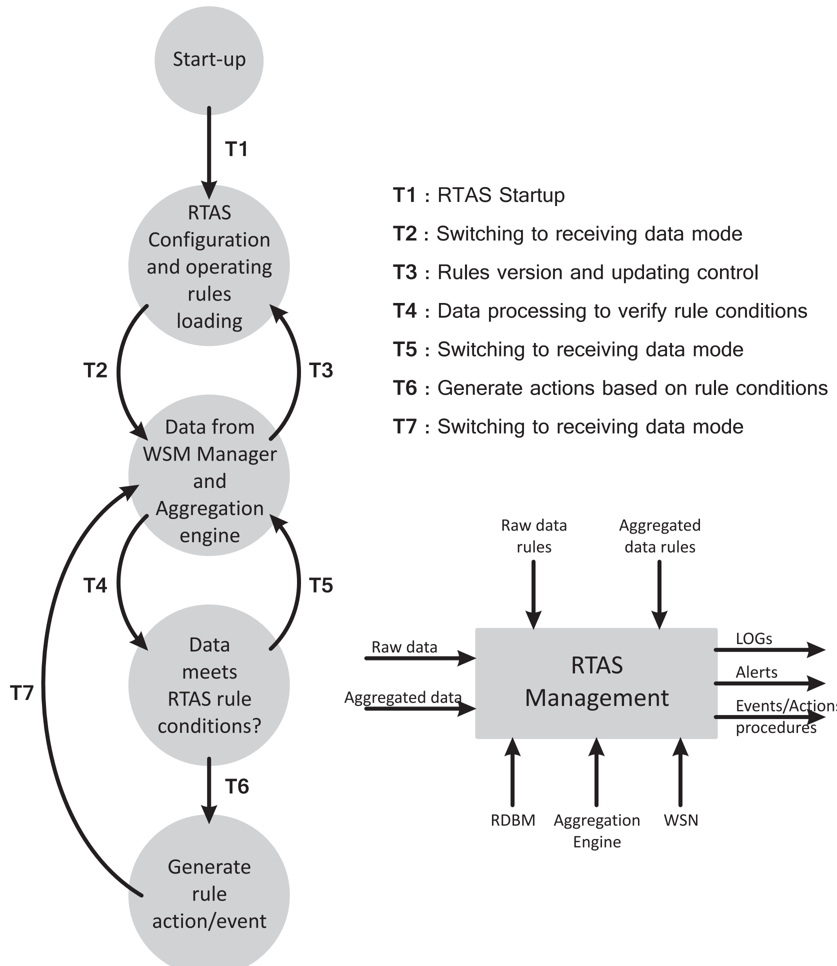

Fig. 6. Functional flowchart of the RTAS operation, including its IDEF (Integration Definition for Function Modeling) conceptual definition.

```
<RULE1><INPUT{Parm1, Parm2, ..., ParmN}>
        <CONDITIONS{Cond1, Cond2, ... , CondN }>
                <ACTIONS{Action1, Action2, ... , ActionN }>
<\RULE1>
```

Listing 1. RTAS Rule conceptual definition.

```
//
//**** Oospore probability rule
//
if ( DOY > 79 && DOY < 301 )
    {
    if ( (TM>9 && TM<12) && (HR>80 && RH<85) && (P>=10))
        {
                java.util.List<java.lang.Object>result = port.setAlert(alert_type);
        }
    }
```

Listing 2. Example of a RTAS rule as a script that can be uploaded to iPAGAT. In this case, the rule is evaluated within DOY (Day of Year) 80 and 300. TM, HR and P stands for temperature, relative humidity and precipitation values. This example is based on Cruz (1982) methodology.

integration interface, as key blocks of the gateway software architecture.

For this purpose, the iPAGAT hardware structure was mounted in the roof of our Engineering Laboratory building in order to establish wireless links to MPWiNodeZ devices deployed according to the map in Fig. 7.

Two of them (referred to as `Malv01` and `Malv02` in Fig. 7) have been used since the start of this experiment in real-time monitoring. They collect micrometeorological parameters in a vineyard (air temperature, relative humidity and solar radiation), to assist in mildew powdery disease modelling. Device `P3` is used to route `Malv01` and `Malv02` data back to the iPAGAT.

```
@WebMethod(operationName = "getSensorData_by")
    public Vector operation(@WebParam(name = "zone")
    String zone, @WebParam(name = "utilisation")
    String utilisation, @WebParam(name = "sensortype")
    String sensortype, @WebParam(name = "timestamp_min")
    String timestamp_min, @WebParam(name = "timestamp_max")
    String timestamp_max)
```

Listing 3. Header of the Java implementation of a Web Service `getSensorData_by` operation.

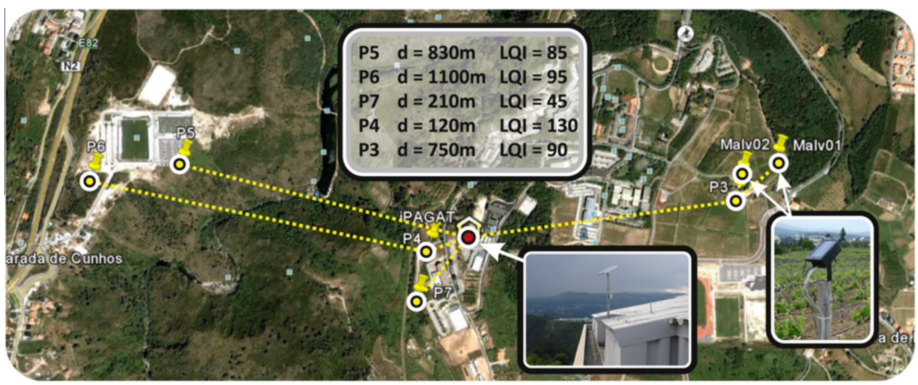

Fig. 7. Network layout of a WSN composed by MPWiNodeZ devices. Devices P3, P4, P5, P6 and P7 use a hi-power module, allowing distances over 1 km.

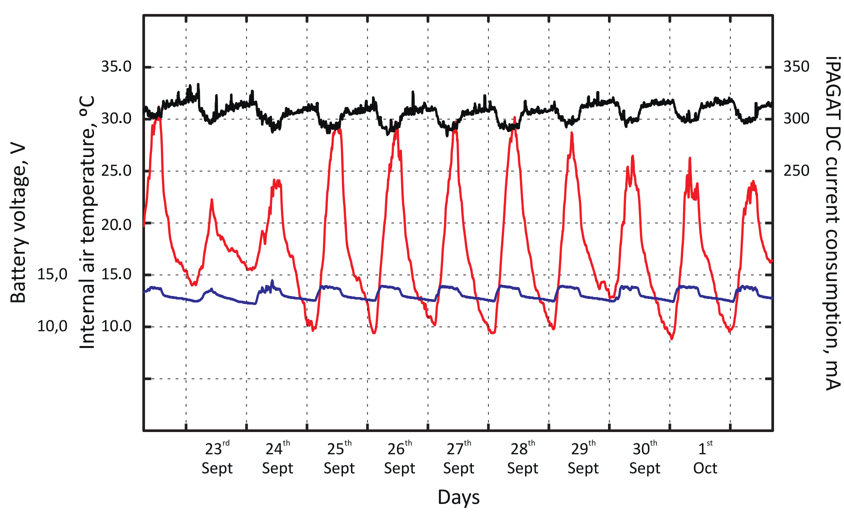

Fig. 8. iPAGAT battery voltage profile and DC current consumption, showing an average value of 300 mA over 12.6 V. On-board temperature is also presented.

The other four devices (`P4`, `P5`, `P6` and `P7`) were installed in more remote locations, in order to evaluate ZigBee Jennic hi-power (+20 dBm) modules (JN5148-001-M04, Jennic, UK) as routing elements of a generic *ad hoc* network based on the MPWiNodeZ platform. In this case, the battery voltage discharging profiles and the Link Quality Indicator (LQI) were recorded by each MPWinodeZ device and routed back to the network coordinator – a part of the iPAGAT system – for storage and post-processing. Network layout, node distances and LQI values are presented in Fig. 7.

4.1. iPAGAT DC current consumption

The iPAGAT is powered by a 40 W solar panel and a 25 Ah capacity battery. With all devices but the Bluetooth dongle turned on, iPAGAT consumes an electrical DC current of approximately 300 mA over 12.6 V, which gives an overall power consumption of 3.78 W. Fig. 8 shows the battery charging/discharging profile as well as the DC current consumption for a 10-day period. iPAGAT housing internal temperature (onboard temperature sensor) is also shown. The Bluetooth discovery service is turned as well as the GPRS modem and the IEEE 802.11 interface.

4.2. iPAGAT data gadget

iPAGAT data can be accessed through its data integration system interface by posing specific queries. Fig. 9 shows a Windows gadget feature used to demonstrate how easily data can be remotely retrieved and visualised directly on a Windows desktop. In the example, the aggregated data summarise relative humidity, air temperature and solar radiation acquired by the `Malv02` node.

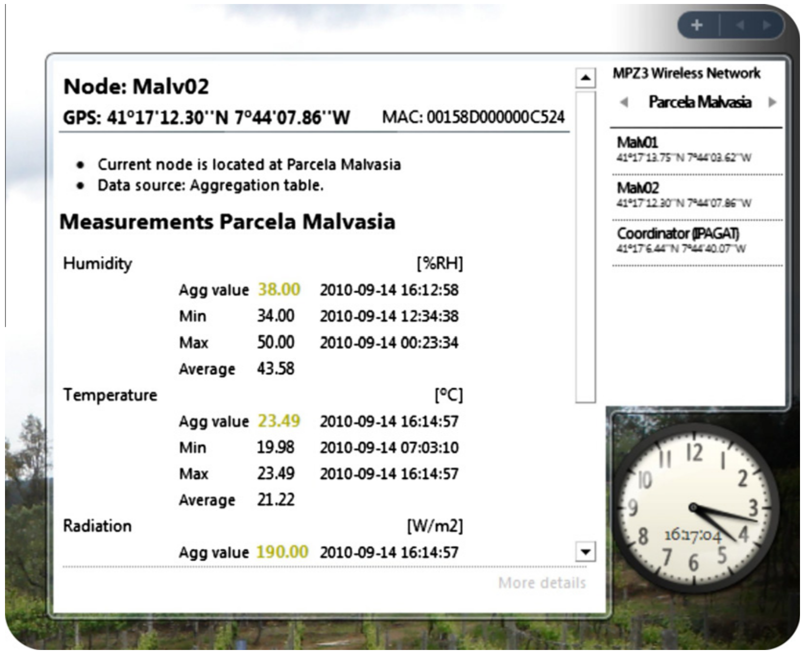

Fig. 9. Screen capture of the Windows gadget used to retrieve and visualise iPAGAT summarised information.

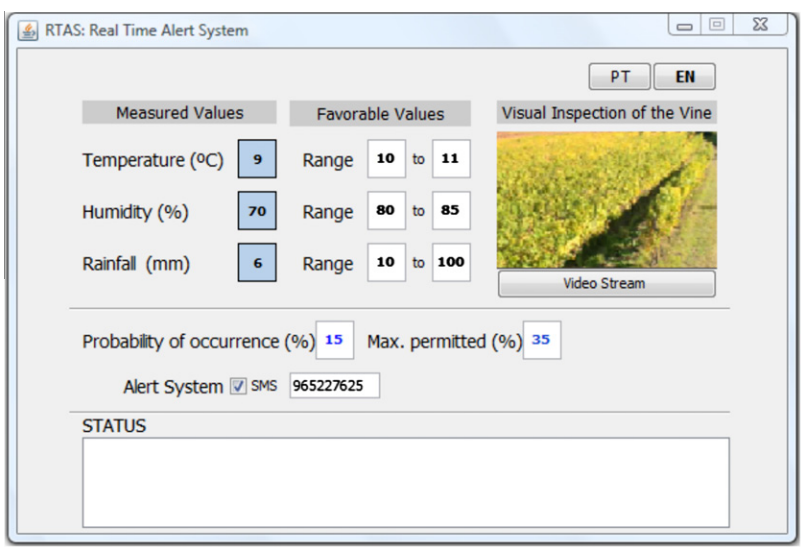

Fig. 10. Screen capture of a simple disease probability monitoring system based on the iPAGAT Real-Time Alert System (RTAS).

4.3. RTAS in disease prediction

To illustrate the advantages of the RTAS embedded in the iPAGAT we developed a simple disease probability monitoring system, depicted in Fig. 10. At the end of each aggregation cycle, each uploaded rule is checked against the aggregated data. The example is based on a mildew disease prediction model Cruz (1982). If the precipitation has been above 10 mm, the zone temperature has been within 10 °C and 11 °C, the relative humidity has remained above 80%, and the rule has been consistently triggered throughout a certain number of days, a warning is generated.

5. Conclusions and discussion

The deployment of a wireless sensor network and its use in the PV context is not straightforward. The acquisition of the raw data is left to a number of typically small, low-power, energy-harvesting devices but decision support systems depend on higher-level data representations. There is a gap between what the low-level devices provide and what the higher levels need. This difficulty can be overcome at a cost (computing power and bandwidth) but as the number of sensors increases, the volume of the raw data and the resources needed become prohibitive.

The iPAGAT gateway was designed to bridge the gap between the sensors and the decision-making. It circumvents the difficulties created by a centralised processing model by providing an intermediate layer between the sensor network and a remote location.

The iPAGAT is deployed in the field and as such it must be autonomous. Our field tests confirm that its power needs can in general be met by harvesting solar energy. The iPAGAT is therefore capable of continuous operation and is fully compatible with the sensor devices used. The testing also showed that several consecutive cloudy days may cause a power failure. We verified that the replacement of the original 25 Ah dry-fit battery with one of higher capacity (A512/55A, Sonnenschein, Germany) considerably reduces the probability of a failure.

The iPAGAT increases the overall intelligence of the sensor network. It runs an aggregation engine and performs intermediate level data processing. By doing so, it distributes the work load. The test results shows that the software architecture and database structure are adequate and that the system performs well even under intensive use.

The communication capabilities of the iPAGAT, which include Bluetooth, IEEE 802.11 and GPRS, have also proven very useful. They allow local and remote users to access the Internet, but, more importantly, they make it possible for users located in the field to access gateway and remote data, using authenticated smartphones. This flexibility opens up the way for further developments and applications, some of which we have already begin to discuss (Cunha et al., 2010).

Our field experiments and tests provide convincing evidence that iPAGAT represents an important step forward in the development of distributed service-oriented information systems for precision agriculture applications.

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