Distributed Monitoring Systems for Agriculture based on Wireless Sensor Network Technology

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***Abstract*—The adoption of Wireless Sensor Networks (WSN) for wide area environmental monitoring is currently considered one of the most challenging application scenarios for this emerging technology. The promise of an unmanaged, self-configuring and self-powered wireless infrastructure, with a continuously decreasing cost per unit, attracts the attention of both final users and system integrators, replacing previously deployed wired solutions and opening new business opportunities. Agricultural scenarios seem to be one of the most promising application areas for WSN due to the necessity of improving the agro-food production chain in terms of precision and quality. This involves a careful system design, since a rural scenario consists of an extensive area devoid of an electrical power supply and availabile wired connections. This paper shows and describes a practical case study, starting from a real problem and reaching the best architectural solutions with particular focus on hardware implementation and communication protocol design. Moreover, encouraging and unprecedented results are shown, achieved with this approach and supported by several pilot sites in different vineyards throughout Italy and France. Finally, the commercial system ”VineSense”, born from previous experimental solutions, and its agronomic results are also presented.**

***Keywords*-Wireless Sensor Network, Distributed Agricultural Monitoring, Hardware and Protocol Design, Physiology and Pathogens Control, Pilot Sites.**

I. Introduction

Agriculture is one of the most ancient activities of man in which innovation and technology are usually accepted with difficultly, unless real and immediate solutions are found for specific problems or for improving production and quality. Nevertheless, a new approach, of gathering information from the environment, could represent an important step towards high quality and ecosustainable agriculture.

Nowadays, irrigation, fertilization and pesticides management are often left to the farmer and agronomist's discretion: common criteria used to guarantee safe culture and plant growth is often giving a greater amount of chemicals and water than necessary. There is no direct feedback between the decision of treating or irrigating plants and the real effects in the field. Plant conditions are usually committed to sporadic and faraway weather stations which cannot provide accurate and local measurements of the fundamental parameters in each zone of the field. Also, agronomic models, based on these monitored data, cannot provide reliable information. On the contrary, agriculture needs detailed monitoring in order to obtain real time feedback between plants, local climate conditions and man's decisions.

The most suitable technology to fit an invasive method of monitoring the environment is a *Wireless Sensor Network* (WSN) system [2].

The requirements that adopting a WSN are expected to satisfy in effective agricultural monitoring concern both *system level* issues (i.e., unattended operation, maximum network life time, adaptability or even self-reconfigurability of functionalities and protocols) and *final user* needs (i.e., communication reliability and robustness, user friendly, versatile and powerful graphical user interfaces). The most relevant mainly concerns the supply of *stand-alone* operations. To this end, the system must be able to run unattended for a long period, as nodes are expected to be deployed in zones that are difficult to maintain. This calls for optimal energy management. An additional requirement is *robust* operative conditions, which needs fault management since a node may fail for several reasons. Other important properties are scalability and adaptability of the network's topology, in terms of the number of nodes and their density in unexpected events with a higher degree of responsiveness and reconfigurability. Finally, several user-oriented attributes, including fairness, latency, throughput and enhanced data querying schemes [3] need to be taken into account even if they could be considered secondary with respect to our application purposes because the WSN's cost/performance trade-off [4].

The before mentioned requirements call for a carefully designed and optimized overall system for the case study under consideration.

In this paper an end-to-end monitoring solution is presented [1], joining hardware optimization with communications protocols design and a suitable interface. In particular, Section II provides an overview of the related works. Section III presents the overall system in terms of hardware, protocol and software design. Section IV describes the real experiences, focusing on several case studies analyses for highlighting the effectiveness and accurateness of the developed system. Section V and Section VI describe respectively the commercial system "VineSense", born from the experimental solution, and some agronomic results. Finally, in Section VII some conclusions are drawn in order to explain the future direction of the current research study.

II. Related Works

The concept of precision agriculture has been around for some time now.

Starting from 1994, Blackmore et al. [5] defined it as a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental quality. The early adopters during that time found precision agriculture to be unprofitable. Moreover they found the instances of implementation of precision agriculture were few and far between. Further, the high initial investment in the form of electronic equipment for sensing and communication meant that only large farms could afford it. The technologies proposed at that point comprised of three aspects: *Remote Sensing* (RS), *Global Positioning System* (GPS) and *Geographical Information System* (GIS). RS coupled with GPS coordinates produced accurate maps and models of the agricultural fields. The sampling was typically through electronic sensors such as soil probes and remote optical scanners from satellites. The collection of such data in the form of electronic computer databases gave birth to the GIS. Statistical analyses were then conducted on the data and the variability of agricultural land with respect to its properties was charted. The technology apart from being non real-time, involved the use of expensive technologies like satellite sensing and was labor intensive where the maps charting the agricultural fields were mostly manually done.

Over the last seven years, the advancement in sensing and communication technologies has significantly brought down the cost of deployment and running of a feasible precision agriculture framework. Emerging wireless technologies with low power needs and low data rate capabilities, which perfectly suites precision agriculture, have been developed [6].

The sensing and communication can now be done on a real-time basis leading to better response times. The wireless sensors are cheap enough for wide spread deployment in the form of a mesh network and offers robust communication through redundant propagation paths [7]. Wireless sensor networks allow faster deployment and installation of various types of sensors because many of these networks provide self-organizing, self-configuring, self-diagnosing and self-healing capabilities to the sensor nodes.

The applications using wireless sensor technology for precision agriculture are briefly explored below.

Cugati et al. [8] developed an automated fertilizer applicator for tree crops. The system consisted of an input module for GPS and real-time sensor data acquisition, a decision module for calculating the optimal quantity and spread pattern for a fertilizer, and an output module to regulate the fertilizer application rate. Data communications among the modules were established using a Bluetooth network.

Evans and Bergman [9] are leading a USDA research group to study precision irrigation control of self-propelled, linear-move and center-pivot irrigation systems. Wireless sensors were used in the system to assist irrigation scheduling using combined on-site weather data, remotely sensed data and grower preferences.

The US Department of Agriculture (USDA) [10] conducted a research in Mississippi to develop a high-speed wireless networking system to help farmers download aerial images via WLAN to their PCs, laptops or PDAs. The images were mainly used for precision farming applications.

Mahan and Wanjura [11] cooperated with a private company to develop a wireless, infrared thermometer system for in-field data collection. The system consisted of infrared sensors, programmable logic controllers and low power radio transceivers to collect data in the field and transmit it to a remote receiver outside the field.

The Institut Für Chemie und Dynamik der Geosphäre [12] developed a soil moisture sensor network for monitoring soil water content changes at high spatial and temporal scale.

III. Overall System Characterization

The overall system is shown in Figure 1. It is comprised of a self-organizing WSN endowed with sensing capabilities, a GPRS Gateway which gathers data and provides a TCP-IP based connection toward a Remote Server and a Web Application which manages information and makes the final user capable of monitoring and interacting with the instrumented environment.

In the following subsections, an end-to-end system description of the hardware, protocol and software design is presented.

A. Hardware Design

Focusing on an end-to-end system architecture, every constitutive element has to be selected according to the application requirements and scenario issues, especially the hardware platform. Many details have to be considered, involving the energetic consumption of the sensor readings, the power-on and power-save states management and a good trade-off between the maximum radio coverage and the transmitted power. After an accurate investigation of the out-of-the-shelf solutions, accordingly to these constraints and to the reference scenarios, 868 MHz *Mica2* motes [13] were adopted. The *Tiny Operative System* (TinyOS), running

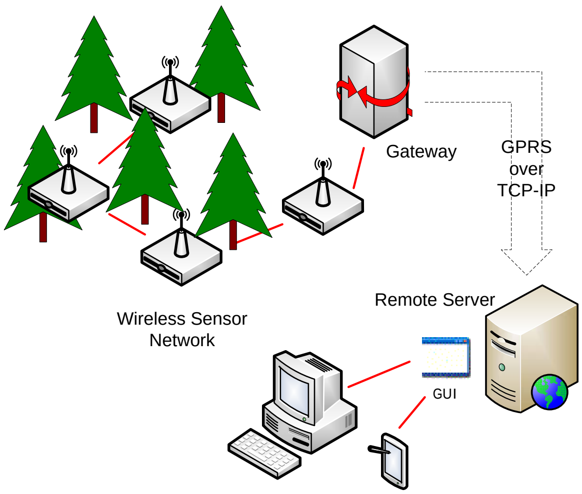


Figure 1. Wireless Sensor Network System.

on this platform, ensures a full control of mote communication capabilities to attain optimized power management and provides necessary system portability towards future hardware advancements or changes. Nevertheless, *Mica2* motes are far from perfection especially in the RF section, since the power provided by the transceiver (*Chipcon CC1000*) is not completely available for transmission, but it is lost to imperfect coupling with the antenna, thus reducing the radio coverage area. An improvement of this section was performed, using more suitable antennas and coupling circuits and increasing the transmitting power with a power amplifier, thus increasing the output power up to 15 dBm, respecting international restrictions and standards. These optimizations allow for a larger radio coverage (about 200 m) and better power management. In order to manage different kinds of sensors, a compliant sensor board was adopted, allowing up to 16 sensor plugs on the same node, this makes a single mote capable of sensing many environmental parameters at a time [14]. Sensor boards recognize the sensors and send *Transducer Electronic Datasheets* (TEDS) through the network up to the server, making an automatic sensor recognition possible by the system. The overall node stack architecture is shown in Figure 2.

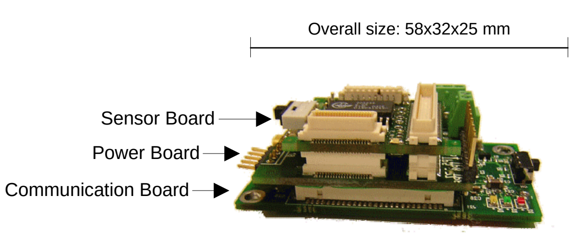


Figure 2. Node Stack Architecture.

The *GPRS embedded Gateway* [15], shown in Figure 3, is a stand-alone communication platform designed to provide transparent bi-directional wireless TCP-IP connectivity for remote monitoring in conjunction with *Remote Data Acquisition* (RDA) equipment, such as WSN where it acts when connected with a Master node or when directly connected to sensors and transducers (i.e., Stand-Alone weather station, Stand-Alone monitoring camera). The Gateway can be

Figure 3. GPRS Gateway.

configured to operate in several ways like "*always on*", "*on demand*", or "*periodically* connected". The Gateway subsystem has been designed to operate unattended, in outdoor environments, since there is usually no access to a power supply infrastructure. Therefore, the hardware design has been oriented to implement low power operating modalities, using a 12 V rechargeable battery and a 20 W solar panel. Data between the Gateway and Protocol Handler are carried out over TCP-IP communication and encapsulated in a custom protocol; from both local and remote interfaces it is also possible to access part of the Gateway's configuration settings.

B. Protocol Design

The most relevant system requirements, which lead the design of an efficient Medium Access Control (MAC) and Routing protocol for an environmental monitoring WSN, mainly concern power consumption issues and the possiblity of a quick set-up and end-to-end communication infrastructure that supports both synchronous and asynchronous queries. The most relevant challenge is to make a system capable of running unattended for a long period, as nodes are expected to be deployed in zones that are difficult to maintain. This calls for optimal energy management since a limited resource and node failure may compromise WSN connectivity. Therefore, the MAC and the network layer must be perfected ensuring that the energy used is directly related to the amount of handled traffic and not to the overall working time.

Other important properties are scalability and adaptability of network topology, in terms of number of nodes and their density. As a matter of fact, some nodes may either be turned off may join the network afterward.

Taking these requirements into account, a MAC protocol and a routing protocol were implemented.

1) MAC Layer Protocol: Taking the IEEE 802.11 *Distributed Coordination Function* (DCF) [16] as a starting point, several more energy efficient techniques have been proposed in literature to avoid excessive power waste due to so called idle listening. They are based on periodical preamble sampling performed at the receiver side in order to leave a *low power* state and receive the incoming messages, as in the WiseMAC protocol [17]. Deriving from the classical contention-based scheme, several protocols (S-MAC [18], T-MAC [19] and DMAC [20]) have been proposed to address the overhead idle listening by synchronizing the nodes and implementing a duty cycle within each slot.

Resorting to the above considerations, a class of MAC protocols was derived, named *Synchronous Transmission Asynchronous Reception* (STAR) which is particularly suited for a *flat* network topology and benefits from both WiseMAC and S-MAC schemes. More specifically, due to the introduction of a duty-cycle, it joins the power saving capability together with the advantages provided by the offset scheduling, without excessive overhead signaling. According to the STAR MAC protocol, each node might be either in an idle mode, in which it remains for a time interval T_l (*listening time*), or in an energy saving sleeping state for a T_s (*sleeping time*). The transitions between states are synchronous with a period *frame* equal to $T_f = T_l + T_s$ partitioned in two sub-intervals; as a consequence, a *duty-cycle* function can also be introduced:

$$d = \frac{T_l}{T_l + T_s} \quad (1)$$

To provide the network with full communication capabilities, all the nodes need to be *weakly synchronized*, meaning that they are aware at least of the awaking time of all their neighbors. To this end, as Figure 4 shows, a node sends a *synchronization message* (SYNC) frame by frame to each of its neighbor nodes known to be in the listening mode (Synchronous Transmission), whereas, during the set-up phase in which each node discovers the network topology, the control messages are asynchronously broadcasted. On the other hand, its neighbors periodically awake and enter the listening state independently (Asynchronous Reception). The header of the synchronization message contains the following fields: a unique node identifier, the message sequence number and the *phase*, or the time interval after which the sender claims to be in the listening status waiting for both synchronization and data messages from its neighbors. The phase ϕ is evaluated according to the following rule:

$$\phi_1 = \tau - T_l \quad (2)$$

if the node is in the sleeping mode, where τ is the time remaining to the next frame beginning. Conversely, if the mote is in the listening status, ϕ is computed as:

$$\phi_2 = \tau + T_s \quad (3)$$

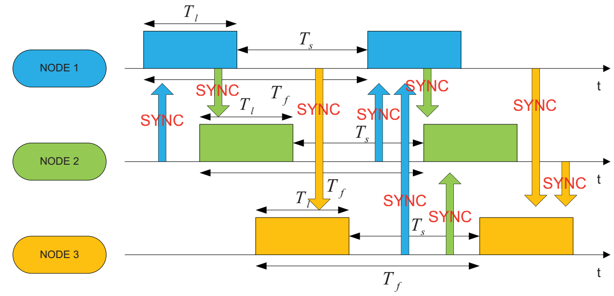


Figure 4. STAR MAC Protocol Synchronization Messages Exchange.

Table I
POWER CONSUMPTION PARAMETERS FOR THE CONSIDERED PLATFORM.

c_{rx}	12 mA
c_{sleep}	0.01 mA
C_{tx}	30 mAh
c_{tx}	0.001 mA

In order to fully characterize the STAR MAC approach, the related energy cost normalized can be evaluated as it follows:

$$C = c_{rx} d T_f + c_{sleep}[T_f(1-d) - NT_{pkt}] + NC_{tx} \quad [mAh]$$

where c_{sleep} and c_{rx} represent the sleeping and the receiving costs $[mA]$ and C_{tx} is the single packet transmission costs $[mAh]$, while T_{rx} and T_s are the receiving and sleeping times $[s]$, T_{pkt} is the synchronization packet time length $[s]$ and finally N is the number of neighbors. When the following inequality is hold:

$$NT_{pkt} \ll T_f$$

then:

$$C \simeq c_{rx} d T_f + c_{sleep} T_f (1-d) + NC_{tx} \quad [mAh]$$

The protocol cost normalized to the synchronization time is finally:

$$\frac{C}{T_f} = c_{rx} d + c_{sleep}(1-d) + \frac{NC_{tx}}{Tf} \quad [mA] \quad (4)$$

As highlighted in Table I, it usually happens that $c_{tx} \ll c_{sleep} \ll c_{rx}$, where $c_{tx} = C_{tx}/T_{pkt}$ and T_{pkt} is the packet transmission time $[s]$ assumed equal to $100\ ms$ as worst case. This means that the major contribution to the overall cost is represented by the listening period that the STAR MAC protocol tries to suitably minimize.

In Figure 5(a) the normalized cost versus the number of neighbor nodes is shown for the S-MAC and STAR MAC schemes. It is worth noticing that the performance of the proposed protocol is better with respect to the existing

Table II
ROUTING TABLE GENERAL STRUCTURE.

Target	NH	HC	PH	LQ	BL	CL
Sink 1	A	N_A	ϕ_A	η_A	B_A	C_A
	B	N_B	ϕ_B	η_B	B_B	C_B
Sink 2	C	N_C	ϕ_C	η_C	B_C	C_C
	D	N_D	ϕ_D	η_D	B_D	C_D

approach for a number of neighbor nodes greater than 7. Finally, in Figure 5(b) the normalized costs of S-MAC and STAR MAC approaches are compared with respect to the duty cycle duration for a number of neighbor nodes equal to 8. It is possible to notice that for $d < 3.5\%$ the proposed protocol provide a significant gain.

2) Network Layer Protocol: In order to evaluate the capability of the proposed MAC scheme in establishing effective end-to-end communications within a WSN, a routing protocol was introduced and integrated according to the *cross layer* design principle [21]. In particular, we refer to a proactive algorithm belonging to the class link-state protocol that enhance the capabilities of the *Link Estimation Parent Selection* (LEPS) protocol. It is based on periodically information needed for building and maintaining the local routing table, depicted in Table II. However, our approach resorts both to the signaling introduced by the MAC layer (i.e., synchronization message) and by the Network layer (i.e., ping message), with the aim of minimizing the overhead and make the system more adaptive in a cross layer fashion. In particular, the parameters transmitted along a MAC synchronization message, with period T_f, are the following:

- *next hop* (NH) to reach the gateway, that is, the MAC address of the one hop neighbor;
- *distance* (HC) to the gateway in terms of number of needed hops;
- *phase* (PH) that is the schedule time at which the neighbor enter in listening mode according to (2) and (3);
- *link quality* (LQ) estimation as the ratio of correctly received and the expected synchronization messages from a certain neighbor.

On the other hand, the parameters related to long-term phenomena are carried out by the ping messages, with period $T_p \gg T_f$, in order to avoid unnecessary control traffics and, thus, reducing congestion. Particularly, they are:

- *battery level* (BL) (i.e., an estimation of the energy available at that node);
- *congestion level* (CL) in terms of the ratio between the number of packets present in the local buffer and the maximum number of packets to be stored in.

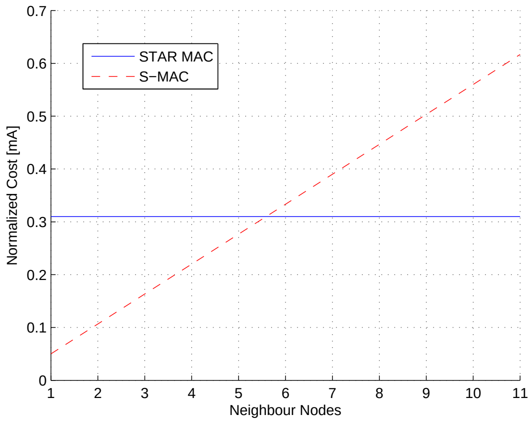
Once, the routing table has been filled with these parameters, it is possible to derive the proper metric by means of a weighted summation of them. It is worth mentioning that the routing table might indicate more than one destination (*sink*) thanks to the ping messages that keep trace of the intermediate nodes within the message header.

C. Software and End User Interface Design

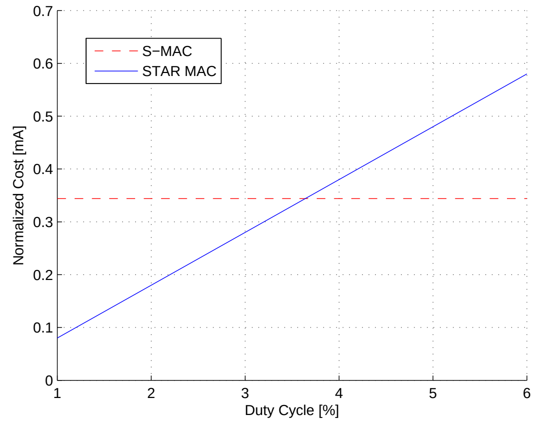
The software implementation was developed, considering a node as both a single element in charge of accomplishing prearranged tasks and as a part of a complex network in which each component plays a crucial role in the network's maintenance. As far as the former aspect is concerned, several TinyOS modules were implemented for managing high and low power states and for realizing a finite state machine, querying sensors at fixed intervals and achieving anti-blocking procedures, in order to avoid software failure or deadlocks and provide a robust stand alone system. On the other hand, the node has to interact with neighbors and provide adequate connectivity to carry the messages through the network, regardless of the destination. Consequently, additional modules were developed according to a cross layer approach that are in charge of managing STAR MAC and multihop protocols. Furthermore, other modules are responsible for handling and forwarding messages, coming from other nodes or from the gateway itself. Messages are not only sensing (i.e., measures, battery level) but also control and management messages (i.e., synchronization, node reset). As a result, a full interaction between the final user and the WSN is guaranteed.

The final user may check the system status through graphical user interface (GUI) accessible via web. After the log-in phase, the user can select the proper pilot site. For each site the deployed WSN together with the gateway is schematically represented through an interactive map. In addition to this, the related sensors display individual or aggregate time diagrams for each node with an adjustable time interval (Start/Stop) for the observation. System monitoring could be performed both at a high level with a user friendly GUI and at a low level by means of message logging.

Figure 6 shows some friendly Flash Player applications that, based on mathematical models, analyze the entire amount of data in a selectable period and provide ready-to-use information. Figure 6(a) specifically shows the aggregate data models for three macro-parameters, such as vineyard water management, plant physiological activity and pest management. The application, using cross light colors for each parameter, points out normal (green), mild (yellow) or heavy (red) stress conditions and provides suggestions to the farmer on how to apply pesticides or water in a certain part of the vineyard. Figure 6(b) shows a graphical representation of the soil moisture measurement. Soil moisture sensors positioned at different depths in the vineyard make it possible to verify whether a summer rain runs off on the soil surface or seeps into the earth and provokes beneficial effects on the plants: this can be appreciated with a rapid look at the soil moisture aggregate report which, shows the



(a) Normalized Cost vs. Neighbor Nodes.



(b) Normalized Cost vs. Duty Cycle Duration.

Figure 5. STAR MAC Performance

moisture sensors at two depths with the moisture differences colore in green tones. Finally, Figure 6(c) highlights stress conditions on plants, due to dry soil and/or to hot weather thanks to the accurate trunk diametric growth sensor that can follow each minimal variation in the trunk giving important information on plant living activity.

IV. Real World Experiences

The WSN system described above was developed and deployed in three pilot sites and in a greenhouse. Since 2005, an amount of 198 sensors and 50 nodes have continuously sent data to a remote server. The collected data represents a unique database of information on grape growth useful for investigating the differences between cultivation procedures, environments and treatments.

A. Pilot Sites Description

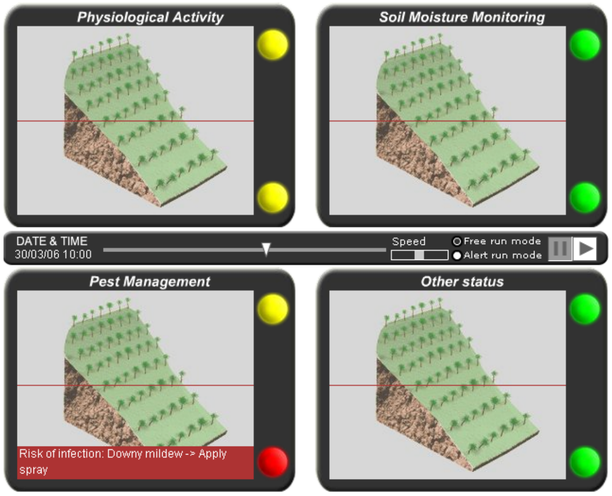
The first pilot site was deployed in November 2005 on a sloped vineyard of the Montepaldi farm in Chianti Area (Tuscany - Italy). The vineyard is a wide area where 13 nodes (including the master node) with 24 sensors, running STAR MAC and dynamic routing protocols were successfully deployed. The deployment took place in two different steps: during the first one, 6 nodes (nodes 9,10,14,15,16,17) were placed to perform an exhaustive one week test. The most important result regards the multi-hop routing efficiency, estimated as:

$$\eta_{MHop} = \frac{M_{EU}}{M_{ex}} \quad (5)$$

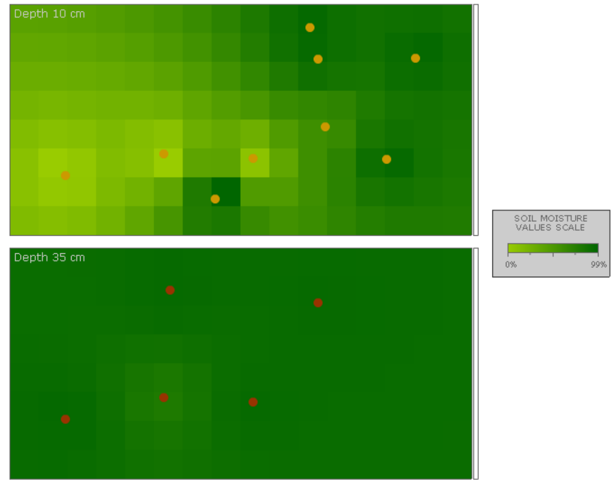
where η_{MHop} is the efficiency, M_{EU} are the messages correctly received by the remote user and M_{ex} are the expected transmitted messages. For the gateway neighbors, η_{MHop} is very high, over 90%. However, even nodes far from the gateway (i.e., concerning an end-to-end multihop path) show a message delivery rate (MDR) of over 80%. This means that the implemented routing protocol does not affect communication reliability. After the second deployment, in which nodes 11,12,13,18,19,20 were arranged, the increased number of collisions changed the global efficiency, thus decreasing the messages that arrived to the end user, except for nodes 18,19,20, in which an upgraded firmware release was implemented. The related results are detailed in Table III. This confirms the robustness of the network installed and the reliability of the adopted communications solution, also considering the power consumption issues: batteries were replaced on March 11^{th} 2006 in order to face the entire farming season. After that, eleven months passed before the first battery replacement occurred on February 11^{th} 2007, confirming our expectations and fully matching the user requirements. The overall Montepaldi system has been running unattended for one year and a half and is going to be a permanent pilot site. So far, nearly 2 million samples from the Montepaldi vineyard have been collected and stored in the server at the University of Florence Information Services Centre (CSIAF), helping agronomist experts improve wine quality through deeper insight on physical phenomena (such

Table III
Message Delivery Rate for the Montepaldi Farm Pilot Site

Location	MDR
Node 9	72.2
Node 10	73.7
Node 11	88.5
Node 12	71.4
Node 13	60.4
Node 14	57.2
Node 15	45.6
Node 16	45.4
Node 17	92.1
Node 18	87.5
Node 19	84.1



(a) Aggregate Data Models for Vineyard Water Management, Plant Physiological Activity and Pest Management.



(b) Soil Moisture Aggregation Report: the upper map represent soil moisture @ 10 cm in the soil and the lower map represents soil moisture @ 35cm in the vineyard after a slipping rain.

(c) Trunk Diametric Growth Diagram: daily and nightly metabolic phases.

Figure 6. Flash Player User Interface

as weather and soil) and the relationship with grape growth.

The second pilot site was deployed on a farm in the Chianti Classico with 10 nodes and 50 sensors at about 500 m above sea level on a stony hill area of 2.5 hectares. The environmental variations of the the "terroir" have been monitored since July 2007, producing one of the most appreciated wines in the world.

Finally, the third WSN was installed in Southern France in the vineyard of Peach Rouge at Gruissan. High sensor density was established to guarantee measurement redundancy and to provide a deeper knowledge of the phenomena variation in an experimental vineyard where micro-zonation has been applied and where water management experiments have been performed for studying plant reactions and grape quality.

B. Greenhouse

An additional deployment at the University of Florence Greenhouse was performed to let the agronomist experts conduct experiments even in seasons like Fall and Winter, where plants are quiescent, thus breaking free from the natural growth trend. This habitat also creates the opportunity to run several experiments on the test plants, in order to evaluate their responses under different stimuli using in situ sensors.

The greenhouse environmental features are completely different from those of the vineyard: as a matter of fact, the multipath propagation effects become relevant, due to the indoor scenario and the presence of a metal infrastructure. A highly dense node deployment, in terms of both nodes and sensors, might imply an increased network traffic load. Nevertheless, the same node firmware and hardware used in the vineyard are herein adopted; this leads to a resulting star topology as far as end-to-end communications are concerned.

Furthermore, 6 nodes have been in the greenhouse since June 2005, and 30 sensors have constantly monitored air temperature and humidity, plants soil moisture and temperature, differential leaf temperature and trunk diametric growth. The sensing period is equal to 10 minutes, less than the climate/plant parameter variations, providing redundant data storage. The WSN message delivery rate is extremely high: the efficiency is over 95%, showing that a low number of messages are lost.

V. VineSense

The fruitful experience of the three pilot sites was gathered by a new Italian company, Netsens, founded as a spin off of the University of Florence. Netsens has designed a new monitoring system called VineSense based on WSN technology and oriented towards market and user applications.

VineSense exalts the positive characteristics of the experimental system and overcomes the problems encountered in past experiences, thus achieving an important position in the wireless monitoring market.

The first important outcome of the experimental system, enhanced by VineSense is the idea of an end-to-end system. Sensors deployed in the field constantly monitor and send measurements to a remote server throught the WSN. Data can be queried and analyzed by final users thanks to the professional and user-friendly VineSense web interface. Qualified mathematic models are applied to monitoring parameters and provide predictions on diseases and plant growth, increasing agronomists' knowledge, reducing costs, while paving the road for new vineyard management.

VineSense improves many aspects of the experimental system, both in electronics and telecommunications.

The new wireless nodes are smaller, more economical, more robust and suited for vineyard operations with machines and tractors. The electronics is more fault tolerant, easier to install and more energy efficient: only a 2200 mAh lithium battery for 2-3 years of continuous running without human intervation. Radio coverage has been improved up to $350\ m$ and nodes deployment can be easily performed by end users who can rely on a smart installation system with instantaneous radio coverage recognition. Sensors used in the VineSense system are low-cost, state-of-the-art devices designed by Netsens in order to guarantee the best accuracy-reliability-price ratio.

The VineSense wireless-sensor unit is shown in Figure 7.

Figure 7. VineSense Wireless Unit.

Recovery strategies and communication capabilities of the stand-alone GPRS gateway have been improved: in fact, data received by wireless nodes are both forwarded in real time to a remote server and temporarily stored on board in case of abrupt disconnections; moreover, automatic reset and restart procedures avoid possible software deadlocks or GPRS network failures; finally, a high gain antenna guarantees a good GPRS coverage almost everywhere. The GPRS gateway firmware has been implemented to allow the remote management of the acquisition settings, relieving users from the necessity of field maintenance.

In Figure 8 the GPRS gateway with weather sensors is shown.

Figure 8. VineSense GPRS Gateway with Weather Sensors.

The web interface is the last part of VineSense's end-to-end: the great amount of data gathered by the sensors and stored in the database needs a smart analysis tool to become useful and usable. For this reason different instruments are at the disposal of various kinds of users: on one hand, some innovative tools such as control panels for real time monitoring or 2D chromatic maps create a quick and easy approach to the interface; on the other hand, professional plots and data filtering options allow experts or agronomists to study them more closely.

VI. Agronomic Results

The use of VineSense in different scenarios with different agronomic aims has brought a large amount of important results.

When VineSense is adopted to monitor soil moisture positive effects can be obtained for plants and saving water, thus optimizing irrigation schedules. Some examples of this application can be found in systems installed in the Egyptian desert where agriculture is successful only through wise irrigation management. In such a terroir, plants suffer continuous hydric stress during daylight due to high air temperature, low air humidity and hot sandy soils with a low water retention capacity. Water is essential for plant survival and growth, an irrigation delay can be fatal for the seasonal harvest therefore, a reliable monitoring system is necessary. The adoption of VineSense in this scenario immediately resulted in continuous monitoring of the irrigating system, providing an early warning whenever pump failure occurred. On the other hand, the possibility to measure soil moisture at different depths allows agronomists to decide on the right amount of water to provide plants; depending on different day temperatures and soil moisture, pipe schedules can be changed in order to reduce water waste and increase water available for plants.

An example of different pipe schedules is shown in Figure 9 . Originally, the irrigation system was opened

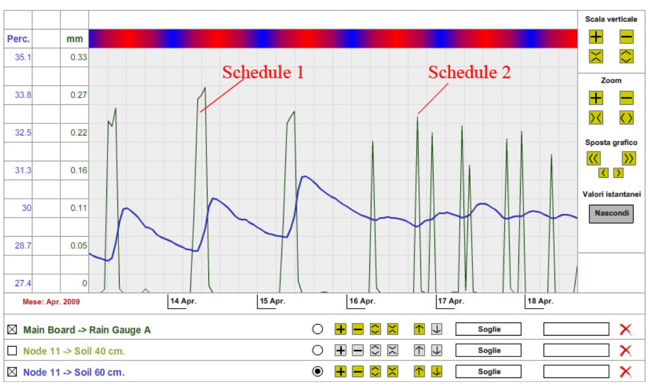


Figure 9. Different Pipe Schedules in Accordance with Soil Moisture Levels.

once a day for 5 hours giving 20 liters per day (schedule 1); since sandy soils reach saturation very rapidly most of this water was wasted in deeper soil layers; afterwards irrigation schedules were changed (schedule 2), giving the same amount of water in two or more times per day; the water remained in upper soil layers at plant root level, reducing wastes and increasing the amount of available water for plants, as highlighted by soil moisture at 60 cm (blue plot).

Another important application of the VineSense system uses the dendrometer to monitor plant physiology. The trunk diametric sensor is a mechanical sensor with $+/-$ 5 microns of accuracy; such an accurate sensor can appreciate stem micro variations occurring during day and night, due to the xilematic flux inside the plant. Wireless nodes measure plant diameter every 15 minutes, an appropriate time interval for following these changes and for creating a plot showing this trend. In normal weather conditions, common physiologic activity can be recognized by agronomists the same as a doctor can do reading an electrocardiogram; when air temperature increases and air humidity falls in combining low soil moisture levels, plants change their activity in order to face water stress, preserve their grapes and especially themselves. This changed behavior can be registered by the dendrometer and plotted in the VineSense interface, warning agronomists about incoming risks; as a consequence, new irrigation schedules can be carried into effect.

Figure 10 shows an example of a plant diametric trend versus air temperature. The blue plot represents the air

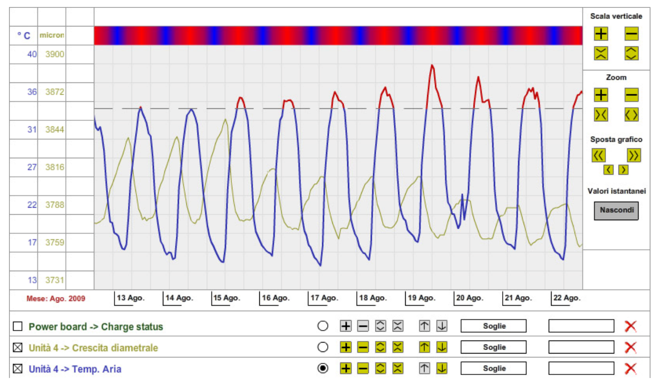


Figure 10. Plant Diametric Trend vs. Air Temperature.

temperature in 10 days, from 13^{th} August until the 22^{nd} August 2009 in Italy; the blue line becomes red when the temperature goes over a 35 degree threshold. During the period in which the temperature is so high, plant stem variations are reduced due to the lower amount of xilematic flux flowing in its vessels, a symptom of water leakage.

WSN in agriculture are also useful for creating new databases with historical data: storing information highlighting peculiarities and differences of vineyards provides agronomists an important archive for better understanding variations in plant production capabilities and grape ripening. Deploying wireless nodes on plants in interesting areas increases the knowledge about a specific vineyard or a specific terroir, thus recording and proving the specificity of a certain wine. I.E., the quality of important wines such CRU, coming from only one specific vineyard, can be easily related to "grape history": data on air temperature and humidity, plant stress, irrigation and rain occurring during the farming season can assess a quality growing process, that can be declared to buyers.

Finally, VineSense can be used to reduce environmental impact thanks to a more optimized management of pesticides in order to reach a sustainable viticulture. Since many of the most virulent vine diseases can grow in wet leaf conditions, it is very important to monitor leaf wetness in a continuous and distributed way. Sensors deployed in different parts of vineyards are a key element for agronomists in monitoring risky conditions: since wetness can change very rapidly during the night in a vineyard and it is not homogeneous in a field, a real time distributed system is the right solution for identifying risky conditions and deciding when and where to apply chemical treatments. As a result, chemicals can be used only when they are strictly necessary and only in small parts of the vineyard where they are really needed, thus reducing the number of treatments per year and decreasing the amount of active substances sprayed in the field and in the environment. In some tests performed in 2009 in Chianti, the amount of pesticides was reduced by 65% compared to the 2008 season.

Figure 11 shows a vineyard map: the green spots are wireless units, distributed in a vineyard of one hectare. Leaf

Figure 11. Distributed Wireless Nodes in a Vineyard.

wetness sensors on nodes 2 and 3 measure different wetness conditions as shown in Figure 12. The upper part of the

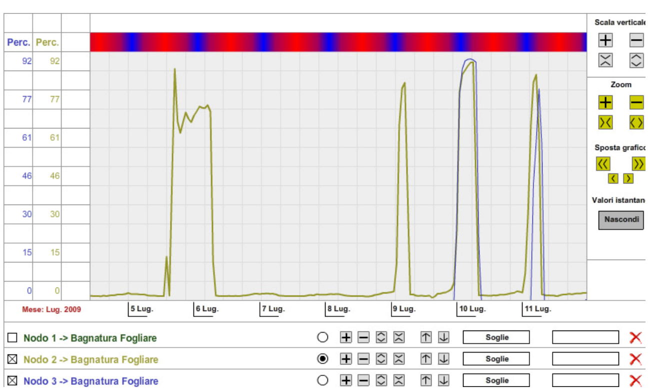


Figure 12. Different Leaf Wetness Conditions in a Small Vineyard.

vineyard is usually wetter (brown plot) than the lower part (blue plot) and sometimes leaf wetness persists for many hours, increasing the risk of attacks on plants.

VII. Conclusion

This paper deals with the design, optimization and development of a practical solution for application to the agro-food chain monitoring and control. The overall system was addressed in terms of the experienced platform, network issues related both to communication protocols between nodes and gateway operations up to the suitable remote user interface. Every constitutive element of the system chain was described in detail in order to point out the features and the remarkable advantages in terms of complexity reduction and usability.

To highlight the effectiveness and accurateness of the developed system, several case studies were presented. Moreover, the encouraging and unprecedented results achieved by this approach and supported by several pilot sites into different vineyard in Italy and France were shown.

The fruitful experience of some pilot sites was gathered by a new Italian company, Netsens, founded as a spin off of the University of Florence. Netsens has designed a new monitoring system called VineSense based on WSN technology and oriented towards market and user applications. In order to point out the improvements of the new solution respect to the experimental one, the main features of VineSense were described. Moreover, some important agronomic results achieved by the use of VineSense in different scenarios were sketched out, thus emphasizing the positive effects of the WSN technology in the agricultural environment.

Nowadays, the application of the solution described in this paper is under investigation to the more general field of environmental monitoring, due to its flexibility, scalability, adaptability and self-reconfigurability.

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