A Climate Control Methodology Based on Wireless Sensor Networks in Greenhouses

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Abstract

This work proposes the design and operation methodologies of a wireless sensor network (WSN) in the greenhouse environment that can lead to the development of an advanced, distributed monitoring and control system. The combined use of conventional sensors with remote sensing technology embedded in a WSN, together with processing algorithms that provide the synthesized information (e.g. performance indicators) required for optimal greenhouse control and decision making, lead to the development of an integrated climate monitoring and control system, towards the realization of precision greenhouse horticulture. Several specific problems related to greenhouse environments are addressed in this work, towards the feasibility of WSNs usage inside the greenhouse, like wireless nodes packaging, standardization of WSN components, electromagnetic fields interference, effects of greenhouse cover materials, etc. The performance of the fine-tuned WSN is evaluated, based on real-time measurements and communication and energy consumption metrics.

INTRODUCTION

Several strongly coupled factors are affecting the inside environmental conditions of a greenhouse, making its climate control a highly complicated task. In modern greenhouses, several measurement points, at plant level, are required to create an objective and detailed representation of the climate at various regions around the covered space. Specific climatic gradients can cause significant differences in terms of yield, productivity, quantitative and qualitative characteristics of the plants, as well as the development of various diseases. To eliminate these differences, a precise and accurate monitoring system is required.

The advancement of sensors technology, in conjunction with that of wireless communication technologies, have led to the development of cheap, relatively easy to install and operate, wireless sensor networks (WSNs), with the field of agriculture being one of their most prominent areas of application. WSNs usually consist of low-cost, low-power, multi-functional sensor nodes that are small in size and communicate over short distances (Akyildiz et al., 2002). They collect sensing information from several points and wirelessly send it, either directly or indirectly, to a base-station that stores it, while some network nodes may also perform data processing and send preprocessed information to the base-station. There are many architectures, communication protocols and energy-management algorithms that have been applied to WSNs to achieve better sensing coverage and mainly to maximize life-duration of the network, as the sensor nodes run on limited battery supply (Ghiasi et al., 2002; Krishnamachari & Ordonez, 2003).

However, in precision agriculture applications, emphasis has been given to the combination of these communication-specific and energy-specific parameters, with application-specific parameters that are imposed by the nature of the particular agricultural application in which the WSN operates (Ferentinos et al., 2005). These application-specific parameters usually concern uniformity and spatial density of sensing points and are defined by specific cultivation characteristics and monitoring requirements (Ferentinos & Tsiligiridis, 2007). Several experimental WSNs have been used in agriculture towards the realization of precision agriculture, mostly in open-field cultivation, but also in greenhouses. Of course, different types and sizes of WSN deployments are suitable for each cultivation system. In greenhouses, which is the application subject of this study, smaller networks are usually used, with an emphasis on precise sensor nodes placement, communication reliability of each specific sensor node, operation difficulties due to the extreme environmental conditions that may occur inside the greenhouse (high values of temperature and relative humidity), etc.

Several monitoring and control applications of WSNs in greenhouses have been recently developed, however most of them are in a prototype stage and have not been specifically designed to meet the exact greenhouse crop needs and overcome the special challenges that arise in a greenhouse environment. Mancuso & Bustaffa (2006) created an experimental monitoring system of a greenhouse with tomato cultivation, equipped with temperature, humidity and soil temperature sensors. Liu et al. (2007) developed a prototype WSN in greenhouses, measuring temperature, humidity and soil moisture, and tested its communication performance. Ahonen et al. (2008) developed a WSN for a commercial greenhouse facility, measuring temperature, humidity, solar radiation and CO_2 concentration. They performed several tests, leading to relative conclusions on the specific issues that arise in a greenhouse WSN application. Cao et al. (2008) used a WSN to measure temperature, humidity and light intensity in three greenhouses and they reported very promising functionality of the setup in terms of communication and data flow quality, expandability, robustness and stability. More recently, Fei-qing et al. (2012) developed a WSN for greenhouse monitoring based on GSM technology, while Park & Park (2011) developed a WSN-based automatic monitoring system to understand the greenhouse environment and state of the crops and optimize growth conditions, with emphasis on crop diseases prevention.

The final goal of the research presented in this paper, is the development of an integrated climate monitoring system for greenhouses that combines information gathered from conventional sensors with the distributed information gathered from specialized WSNs that operate on plant-level. This combination can lead to the creation of synthesized information (e.g., performance indicators, plant stress indices, etc.), which can be used to develop and operate an integrated control system for optimal greenhouse cultivation, realizing the “speaking plant” approach (Hashimoto, 1989). Several specific problems related to the greenhouse environment are addressed in this work, towards the feasibility of WSNs usage inside the greenhouse, like wireless nodes packaging, standardization of WSN components, electromagnetic fields interference, etc. The performance of the fine-tuned WSN is evaluated, as a first step towards the development of the before mentioned integrated monitoring and control system.

MATERIALS AND METHODS

The experiments were conducted in the greenhouses of the University of Thessaly, in Velestino, Greece (39° 44' N, 22° 79' E). The facility has three conventional, single-span, arched greenhouses with plastic cover (polyethylene film), of an area of 160m^2 each (20m by 8m). Natural ventilation is achieved through two side openings and on roof opening, along the long sides. Finally, the greenhouses are equipped with air mixers and fog systems. During the experiments, tomato plants were grown in a hydroponic system with rockwool substrate in one of the greenhouses, while the other two were empty.

Wireless Nodes Characteristics

The WSN prototype was based on the open source, low-power TelosB platform, by UC Berkeley. Specificaly, the motes CM3000 by Advanticsys were used. Wireless communication was achieved with a CC2420 RF chip, which supports 802.15.4 wireless communication at the 2.4-2.48GHz frequency range of the ISM band, with a maximum transfer rate of 250Kbps. TelosB nodes are fully compatible with TinyOS and ContikiOS. Here, TinyOS was chosen and the programming was made in NesC language. In the base-station of the WSN, a mote CM3300 by Advanticsys was used, which contains an amplifier for the wireless circuit that gives it greater communication range and it also has an external power supply option. The base-station also included a PC running on Windows 7, for the collection, storage and processing of the acquired data. The CM3300 node was connected via a USB1000 board (by Advanticsys) to a USB port of the PC.

Greenhouse climate can be very hostile to the sensitive electronics of wireless sensor nodes. For that reason, only external sensor modules were used, while the main computation units were safely enclosed in IP65 humidity resistant boxes. For the air temperature and relative humidity, Sensirion's SHT75 sensor was selected for its high performance, low power consumption and high precision. SHT7x series is very popular in all types of WSN projects and has been extensively used in many agricultural deployments. The ZyTemp TN9 sensor was the second sensor module used. TN9 is a digital, infrared thermocouple, capable of measuring surface and air temperature. The existing TinyOS drivers provided no support for that device, so a custom driver was developed to support the functionality of getting surface temperatures. The low cost of the entire deployment was one of the first priorities and ZyTemp TN9 was selected firstly, because of its performance and low cost against costly industrial products and secondly, for the feasibility of its interconnection with the specific nodes, as presented in numerous publications (Mahan & Yeater, 2008; Evans et al., 2012). Furthermore, other modules were responsible to create the messages and forward them to the base-station.

WSN Deployments

The initial goal was to investigate the performance of the prototype WSN in real greenhouse operation, regarding the communication quality and the energy consumption of the network. For that reason, two different network deployments were tested.

In the first, four wireless nodes were place inside one of the available greenhouse, where tomato plants were grown, in a hydroponic cultivation system. The nodes were placed around each corner of the greenhouse and the base-station was inside the control room, at a distance of 18m from the greenhouse (Fig. 1a). Each node was communicating directly with the base-station, without the use of any clusterhead node in between. The purpose of that deployment was to cover the entire area of a single greenhouse and to investigate the communication and energy efficiency properties of the WSN in the greenhouse conditions and identify possible differences in the performance of each node at different places inside the same greenhouse, taking into account real interference from canopy, greenhouse frame, other surrounding structures, as well as the effects that real plant growing conditions inside a greenhouse could have to the proper operation of the wireless nodes and the communication problems that can arise in such conditions.

In the second deployment, one wireless node was placed in each of the three available greenhouses (Fig. 1b). Each greenhouse had a different cover material and was at a different distance from the base-station, with several obstacles that could influence the communication quality of the network. The main purpose of this experiment was to examine the influence of all these real-application conditions to the communication performance of the network.

RESULTS

The first set of experiments were performed using the first network deployment (Fig. 1a), with four wireless sensors inside one of the greenhouses, at distances of 20 to 28 meters from the base-station. Fig. 2 shows an indicative graph of one of the sensors inside the greenhouse, where values of air temperature, relative humidity and leaf temperature for a period of three days are shown, together with the RSSI values of the sensor, which give indication of its signal strength. It is evident that signal strength seems to be influenced by temperature and relative humidity levels, something that agrees with the results reported by Boano et al. (2010). These correlations were investigated and some relation between RSSI and relative humidity was found, as shown in the graphs of Fig. 3, with a relatively low R^2 value of 0.47 on data from a 24-hour period, but with a better correlation ($R^2 = 0.81$) during a shorter period of measurements. As temperature and relative humidity inside the greenhouse are strongly coupled, further investigation is required in order to estimate the exact influence of each specific parameter to the signal strength of the network nodes.

During the experiments using the first deployment, the relations between battery voltage of the sensors and air temperature and relative humidity inside the greenhouse were also investigated. Fig. 4 shows he average temperature and relative humidity readings of all 4 sensors during a 2-day experiment with a 2-minute measurements acquisition rate, together with the average voltage of the sensor nodes (yellow line). Even though voltage starts to decrease as time passes (because of the energy consumption of the nodes), it is evident that when temperature increases and humidity decreases (in the middle of the graph), voltage drop-rate not only decreases and reaches zero, but absolute voltage values even increase for a while, before they start to decrease again. The same behavior is observed towards the end of the graph. Thus, a strong correlation between battery voltage of the nodes and temperature and humidity values obviously exists.

These correlations are shown in the graphs of Fig. 5. Graph (a) shows the correlation between average sensors voltage and temperature readings inside the greenhouse, for two different periods of the experiment shown in Fig. 4, with different battery levels of the sensors during each period. In both cases, voltage is linearly proportional to temperature, with R^2 values of around 0.96. Similarly, graph (b) shows that voltage is linearly inversely proportional to relative humidity, with similarly high R^2 values. Similarly to the case of RSSI, because of the fact that temperature and relative humidity are strongly coupled, the exact relation of each of them to the values of battery voltage has to be further investigated.

The graphs in Fig. 6 show the correlations of voltage with temperature and relative humidity, for each part of the greenhouse. As shown in Fig. 1a, sensor nodes 1 and 2 were on one side of the greenhouse, while nodes 3 and 4 were on the other side. This separation in the specific correlation analysis was made because slightly different energy consumption rates were observed between the nodes of each greenhouse side. Graph (a) in Fig. 6 shows the response of voltage to temperature change, while graph (b) shows the respective response to relative humidity change. In both cases, the corrections are similar for both sides of the greenhouse, despite the slight difference in nodes' energy consumptions. They are also similar to those reported for the overall average values for the two different periods of the experiment (Fig. 5), with similarly high R^2 values (0.89 – 0.96).

Finally, the effects of real greenhouse setup conditions on the communication performance of the network were examined. The measurements were taken during the second experimental deployment of the WSN (Fig. 1b), where one node was placed in each one of the three greenhouses. Table 1 shows the distance of each sensor node from the base-station and the corresponding greenhouses' cover materials. The results from this experiment showed no significant influence of the cover material to the signal strength of the sensor nodes (expressed as average RSSI values in Table 1), while the distance from the base-station played an important role, as expected. The network operated successfully in these real-application conditions, with very low numbers of lost packets, even though the experiment was conducted with a relatively high rate of measurements acquisition (every 2 minutes).

CONCLUSIONS

A prototype WSN for greenhouse environment distributed monitoring was developed and its communication and energy consumption performances were evaluated in real greenhouse operation conditions. A strong correlation was found between energy consumption of the network and temperature and relative humidity levels inside the greenhouse, while there was some relation between signal strength of the nodes with temperature and relative humidity, which requires further investigation. The type of greenhouse cover plastic material did not seem to influence the communication quality of the WSN, which seemed to be mainly influenced by the distance from the base-station, as expected. Essentially, in the specific greenhouse setup, the WSN operated flawlessly.

As future work, the influence of greenhouse environmental conditions will be further investigated in more detail, while the sensor network itself will be fine-tuned and developed to a final state that can operate unattended for long periods of time in greenhouse facilities. Finally, the network's distributed data will used to develop a more accurate and sophisticated greenhouse management and control system, based on precise spatio-temporal data and specific cultivation performance indicators.

ACKNOWLEDGEMENTS

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Tables

Table 1. Average signal strength and number of lost packets in the three greenhouses.

	Distance from BS	Cover material	Avg RSSI	Lost pack.
Greenhouse 1	25 m	Single layer polyethylene	-64.5 dB	0
Greenhouse 2	12 m	Single layer diffusive pol.	-55.6 dB	3
Greenhouse 3	26 m	Double layer polyethylene	-69.8 dB	10

Figures

(a) (b)

Fig. 1. Schematic representations of the WSN setups in the greenhouse station.

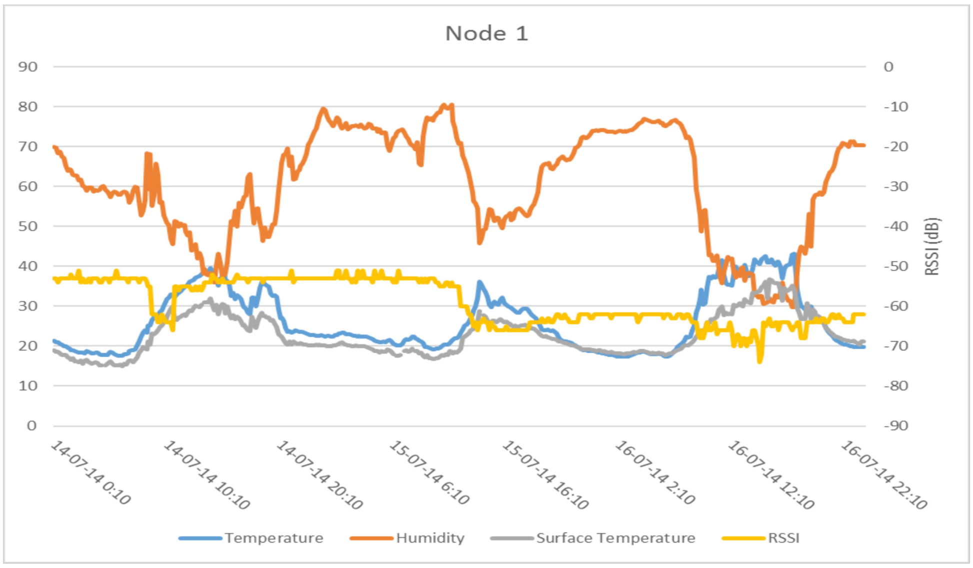


Fig. 2. An indicative graph of one of the wireless sensor nodes.

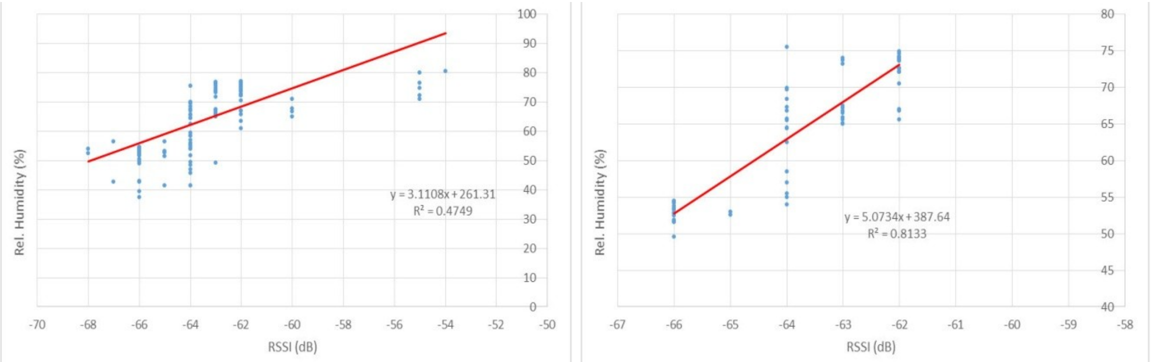


Fig. 3. Sensor's signal strength (RSSI) response to relative humidity, in a 24-hour (left) and a 12-hour interval window (right).

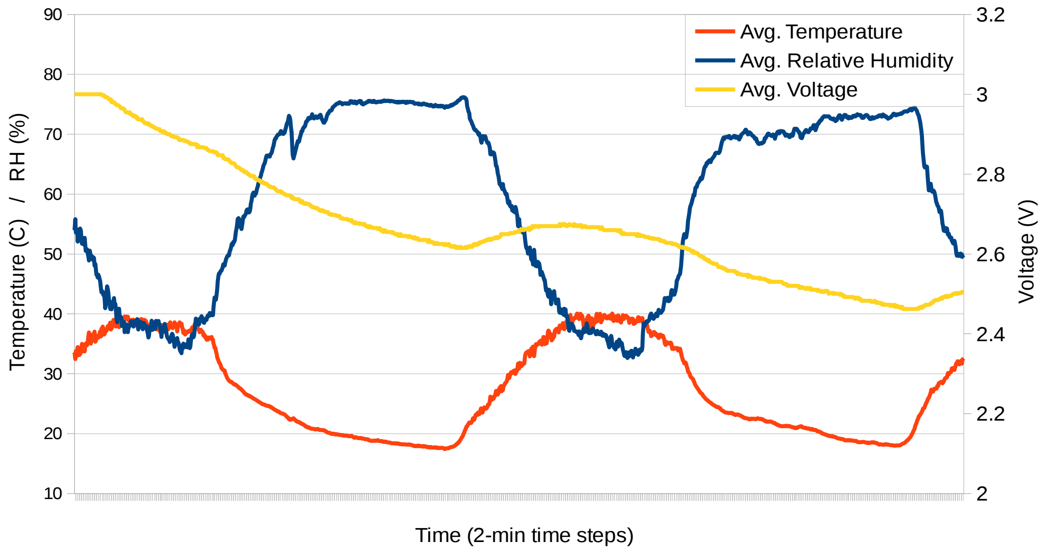
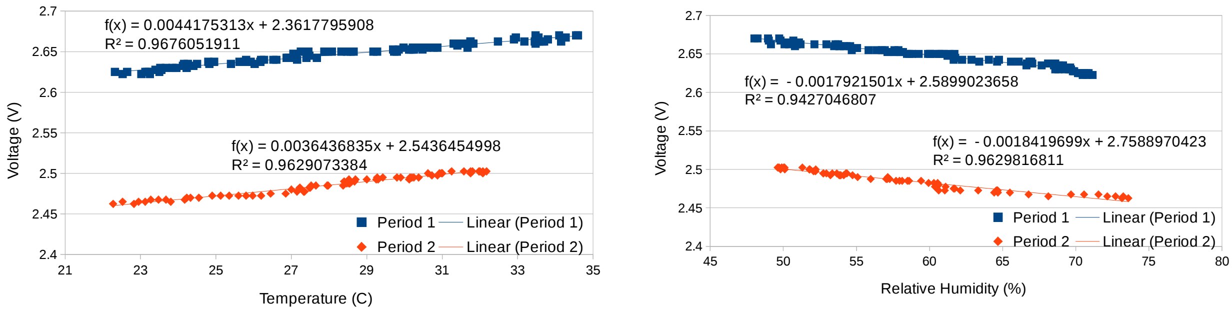
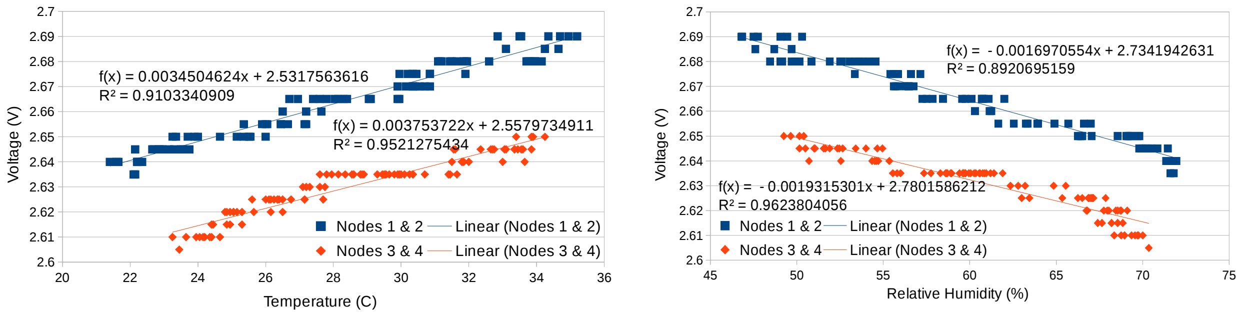


Fig. 4. Average temperature, humidity and battery voltage of the four sensor nodes during a 2-day experiment with the 1st network deployment.



(a) (b)

Fig. 5. Sensors battery voltage response to (a) air temperature and (b) relative humidity levels inside the greenhouse, for two periods of the experiment.



(a) (b)

Fig. 6. Sensors battery voltage response to (a) air temperature and (b) relative humidity levels inside the greenhouse, for the two sides of the greenhouse.