Operation reliability of wireless sensor networks in greenhouse conditions

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Abstract

Wireless sensor networks (WSNs) consist of battery-powered nodes equipped with specific sensors that collect appropriate information and transmit it wirelessly to a central base-station, which stores the received data for future processing or uses it dynamically for monitoring, control or other purposes. Environmental conditions inside a greenhouse can be quite extreme, with high values of temperature and relative humidity and long periods of exposure of the sensor nodes to high solar radiation intensities, which can affect the performance and quality of sensing information of WSNs. In addition, the metallic structure of the greenhouse and the canopy of the cultivated plants also affect WSN operation properties. In this work, the effects of real greenhouse conditions on the reliability of environmental monitoring using a WSN are investigated. Specific issues affecting the performance and accuracy of the WSN are identified and appropriate solutions are proposed. A prototype WSN is developed and installed inside a greenhouse in order to investigate the effects of all these parameters to the operation reliability of the network and assess its performance and the feasibility of possible future operation in a commercial greenhouse. The measured variables are air temperature, relative humidity and radiation intensity. Several experiments are conducted, trying to identify specific problems concerning the accuracy of the measured variables as influenced by specific parameters, as well as the effects of the environmental conditions inside the greenhouse in the operational performance of the WSN.

Keywords: monitoring system, communication performance, controlled environment, hydroponics, plant-based measurements

INTRODUCTION

Precision agriculture (PA) and controlled environment agriculture (CEA) constitute some very prominent areas of application of wireless sensor networks (WSNs). These networks usually consist of battery-powered nodes equipped with specific sensors that collect appropriate information and transmit it wirelessly to a central base-station, which stores the received data for future processing or uses it dynamically for monitoring, control or for other purposes (Akyildiz et al., 2002; López Riquelme et al., 2009; Matese et al., 2009; Li et al., 2010; Vox et al., 2014). The main properties that are crucial to the proper operation of a WSN are: i) sufficient measurements accuracy, ii) reliable network connectivity and iii) low power consumption. Several network architectures, communication protocols and energy-management algorithms have been applied to WSNs to maximize sensing coverage of the network as well as life-duration of the battery-powered sensor nodes (Ghiasi et al., 2002; Krishnamachari and Ordonez, 2003). All of these properties are affected not only by the characteristics of the sensors and the design parameters and communication algorithms of the network, but also by the environmental and physical conditions that the WSN operates in.

PA and CEA introduce several application-specific parameters that have to be considered alongside with communication-specific and energy-specific properties, when

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designing a WSN (Baggio, 2005; Garcia-Sanchez et al., 2011; Ferentinos and Tsiligiridis, 2007; Mancuso and Bustaffa, 2006). The use of WSNs in such applications provides valuable information about the spatial distribution of the monitored variables, which constitutes a very important tool for precise control mainly in PA, but also in large-scale CEA (Balendock et al., 2010). Especially in the case of CEA, which mainly involves the monitoring and control of greenhouse environment, several issues can arise in relation to the sensing quality of the WSNs used, mainly because of the extreme environmental conditions inside a greenhouse (Ferentinos et al., 2015). Such conditions can make the WSN measurements noisy and usually annotated with some measure of uncertainty (Wen et al., 2015). Specifically in the case of greenhouses, 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 respective conclusions on the specific issues that arise in a greenhouse WSN application. Similarly, Balendock et al. (2014) reported problematic behavior of WSNs regarding their sensing accuracy in greenhouse environments in relation to direct radiation.

In this work, the operation reliability and accuracy of WSNs installed in experimental greenhouses are investigated. Specific greenhouse environmental conditions that affect the quality of measured variables are identified and their role in the accuracy of measurements is explored and analyzed. Specific compensation algorithms are proposed for the proper calibration of wireless sensors towards more reliable and accurate monitoring of greenhouse climatic conditions, so that properly tuned WSNs can be used in future CEA applications towards more precise control of greenhouse cultivation systems.

MATERIALS AND METHODS

The experiments were conducted in one of the experimental greenhouses of the University of Thessaly, in Velestino, Greece (39°44’N, 22°79’E). The conventional, single-span, arched greenhouse that was used, has plastic cover (polyethylene film) and a ground area of 160 m^2 (20×8 m). Natural ventilation is achieved through two side openings and a roof opening, along the sides. Finally, the central sensors system includes temperature and relative humidity sensors HD9009TR Hygro-transmitter, Delta OHM, S.r.L., Padova, Italy (accuracy T=±0.1°C, RH=±2%) located at the center of the greenhouse, at approximately 1.8 m above ground. During the experiments, there were not any cultivated plants in the greenhouse, so that the effects of solely the outside environmental disturbances to the greenhouse microclimate can be taken into account, as they affect the operation reliability of the installed WSN.

Wireless nodes characteristics

The WSN prototype was based on the open source, low-power TelosB platform, by UC Berkeley, with TinyOS operating system. Specifically, the motes CM3000 by Advanticsys were used. Wireless communication was achieved with a CC2420 RF chip. 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. 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.

The main computation units of the wireless nodes were safely enclosed in IP65 humidity resistant boxes and external sensor modules were connected to them. For the air temperature and relative humidity, a Sensirion’s SHT75 sensor was selected for its high performance, low power consumption and high precision. For the radiation intensity measurements, SP Lite2 pyranometers were used (by Kipp & Zonen), connected to Wisensys® wireless measuring platform that wirelessly transmitted the measured values to a central base-station. In all the conducted experiments, each node of the WSN was communicating directly with the base-station (single-hop communication), without the use of any cluster head nodes in between. The base-station node was at a distance of about 20 m from the wireless nodes of the network.

WSN operation experiments and initial calibration

Three specially designed experiments were conducted with specific WSN setups inside the greenhouse, each one with specific goals concerning the identification of the effects of greenhouse environmental conditions to sensing reliability and quality of the WSN. In all cases, the main goal was to identify the effect of solar radiation to the accuracy of measurements of the network's sensors and for that reason, three different placements of the WSN nodes were considered: i) inside ventilated boxes specially designed to protect the sensors and the wireless nodes from solar radiation (Figure 1a), labeled as “boxed nodes”, ii) under the shade of some metallic surface (Figure 1b), labeled as “shaded nodes” and iii) unprotected from direct sunlight, labeled as “exposed nodes” (Figure 1b). Temperature and relative humidity values were measured by the wireless nodes, while radiation intensity levels were also recorded at the place of each wireless node. In addition, values of temperature, relative humidity and radiation intensity from the central sensors of the greenhouse control unit were also recorded. The WSN and the portable radiation intensity units were reporting data every 2 min. and their measurements were averaged over 10-minute periods to much the time-step of the central control unit of the greenhouse.

Figure 1. Wireless sensor nodes inside the greenhouse in (a) “boxed” setup and (b) “exposed” and “shaded” setups.

The main goal of the experiments was to investigate the accuracy and reliability of measurements as influenced by sunlight inside the greenhouse. Three different experiments were designed and conducted for that purpose, during a 4-month period, from September to December. During the 1st experiment, four “boxed” nodes were placed in four different places inside the greenhouse and measurements were collected for a period of one week. In the 2nd experiment, the “exposed nodes” setup was used for the same four nodes, while radiation intensity was also measured at the points of the sensor nodes. The experiment lasted for 12 days. Two approaches were followed in the effort to determine in which degree the reliability of the sensor's readings is influenced by solar radiation inside the greenhouse: a) the standard deviations of the measurements between the 4 WSN nodes in each experiment (boxed and exposed nodes) were estimated and correlated with the radiation intensity values, and b) the root mean squared errors (RMSEs) of the WSN measurements based on the greenhouse central sensors were estimated and were also correlated to the radiation intensity values.

Consequently, the 3rd experiment was conducted with the goal of investigating the accuracy and reliability of carefully shaded sensor nodes, by comparing their measurements with those of “boxed” sensor nodes. Two groups of two nodes each were used, one with “boxed” nodes and one with “shaded” nodes. For each group, the standard deviations between the nodes of the group and their RMSEs based on the greenhouse central sensors were estimated and correlated to radiation intensity levels. This specific experiment lasted for 18 days.

RESULTS AND DISCUSSSION

Initially, some preliminary analysis on the accuracy of the sensors of the WSN was conducted to ensure that all nodes were properly calibrated and sufficiently accurate in comparison to the central sensors of the greenhouse. The goal was to develop appropriate empirical functions to calibrate temperature and relative humidity measurements. Thus, initially the WSN was used to take measurements of the greenhouse for a period of one week, using the "boxed nodes" setup for the four available wireless nodes. The temperature measurements of each sensor node were correlated to the temperature measurements of the greenhouse central sensor. An almost linear relation was found for all wireless sensors, with the best fit given by the following second degree polynomials (subscripts correspond to each of the 4 sensor nodes – asterisks denote the calibrated values):

$$T_1^* = -0.02\ T_1^2 + 1.62\ T_1 + 2.87\ (R^2 = 0.90)$$

$$T_2^* = -0.02\ T_2^2 + 1.64\ T_2 + 2.08\ (R^2 = 0.90)$$

$$T_3^* = -0.01\ T_3^2 + 1.38\ T_3 + 4.19\ (R^2 = 0.92)$$

$$T_4^* = -0.02\ T_4^2 + 1.64\ T_4 + 2.04\ (R^2 = 0.90)$$

Based on the measured values of relative humidity during that initial experiment, it was discovered that their accuracy (as compared to the relative humidity values measured by the greenhouse central sensor) was highly correlated to the temperature values. Therefore, a simple compensation algorithm was developed to calibrate the relative humidity readings of the wireless sensors, based on the current temperature inside the greenhouse:

$$RH_1^* = RH_1 - 0.04\ T_g^2 - 0.97\ T_g + 68.44$$

$$RH_2^* = RH_2 - 0.04\ T_g^2 - 0.94\ T_g + 67.25$$

$$RH_3^* = RH_3 - 0.05\ T_g^2 - 0.40\ T_g + 61.77$$

$$RH_4^* = RH_4 - 0.05\ T_g^2 - 0.73\ T_g + 65.22$$

where, RH_i (i=1,4) are the raw relative humidity readings of each sensor node, RH_i^* are the corresponding corrected relative humidity values and T_g is the air temperature according to the greenhouse central sensor.

Figures 2 and 3 show the results of the calibration process for temperature and relative humidity, respectively, during the one-week period of the first experiment. The dramatic improvement of the measured values is evident, especially in the case of relative humidity. During all the specialized experiments, those calibration functions were used for the correction of the WSN measurement values.

The analysis of standard deviations between the values of the four sensor nodes during the first two experiments, shows that spreading between temperature measurements of the four sensors was much greater for higher values of radiation intensity in the case of "exposed" nodes, while in the case of "boxed" nodes the increase of standard deviation of the temperature values was very small with the increase of radiation intensity (Figure 4a). In the case of relative humidity values (Figure 4b), the measurements of the "boxed" nodes seem to be also highly influenced by the intensity of solar radiation, with higher deviation values in the middle values of radiation intensities, while in the case of "exposed" nodes, the spreading in not practically influenced by solar radiation.

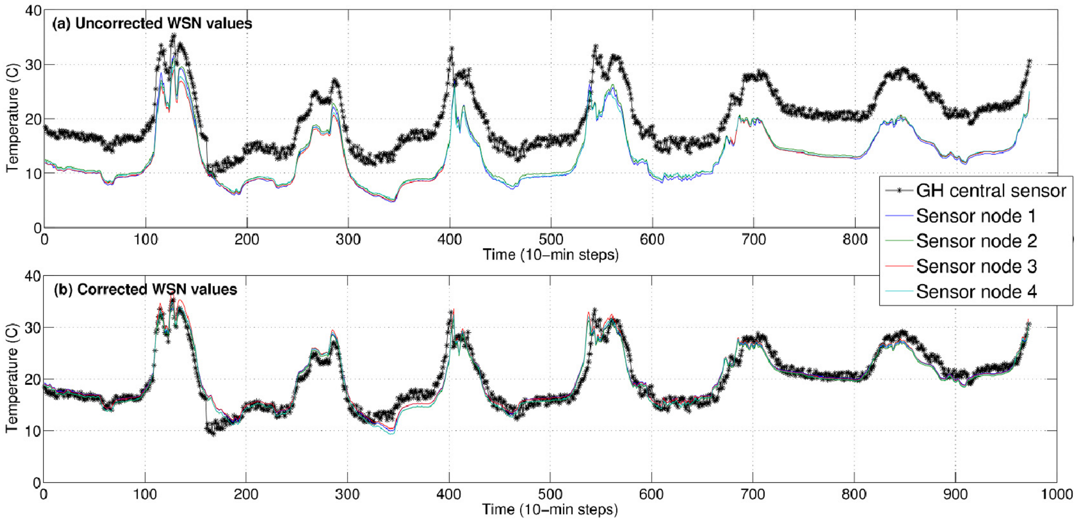

Figure 2. WSN temperature values in relation to greenhouse central sensor values (a) before and (b) after calibration.

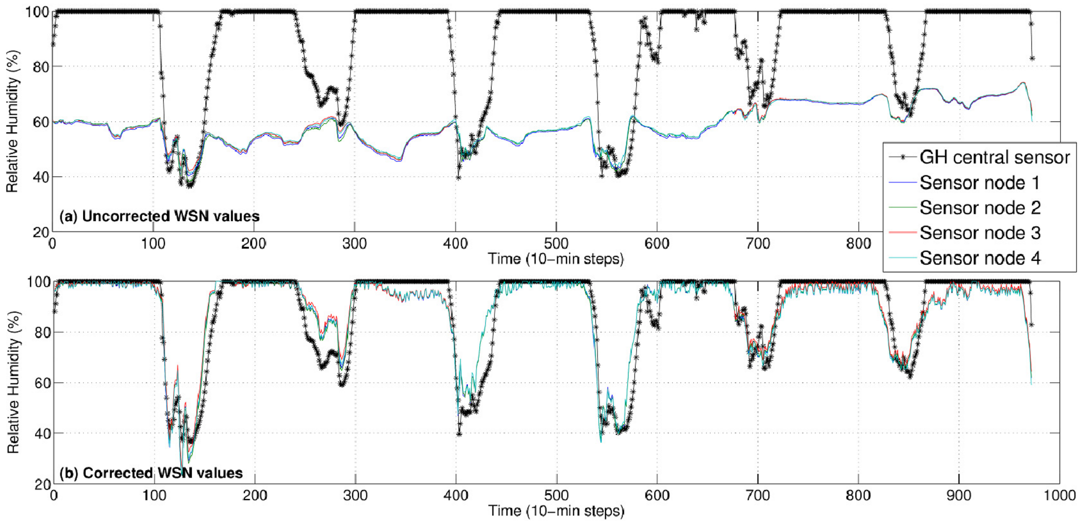

Figure 3. WSN relative humidity values in relation to greenhouse central sensor values (a) before and (b) after calibration.

The analysis of RMSEs shows that, in general, the RMSE of both temperature and relative humidity values of WSN nodes compared to the greenhouse central sensors are much higher in the case of "exposed" nodes. In the case of temperature values (Figure 5a), there is not any obvious correlation of the RMSEs of the "exposed" sensors with the values of radiation intensity, while in the case of relative humidity (Figure 5b), the errors seem to be slightly increasing at higher radiation intensities.

Thus, temperature and relative humidity measurements reliability is drastically influenced by solar radiation intensity, making not properly protected wireless sensor nodes highly unreliable for measuring greenhouse environmental conditions.

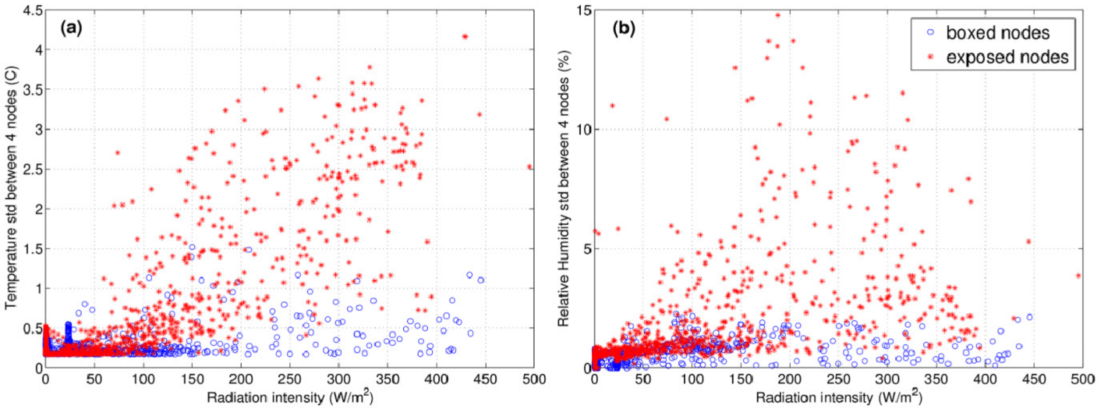

Figure 4. (a) Temperature and (b) relative humidity standard deviations between 4 sensor nodes versus radiation levels, in cases of "boxed" and "exposed" nodes.

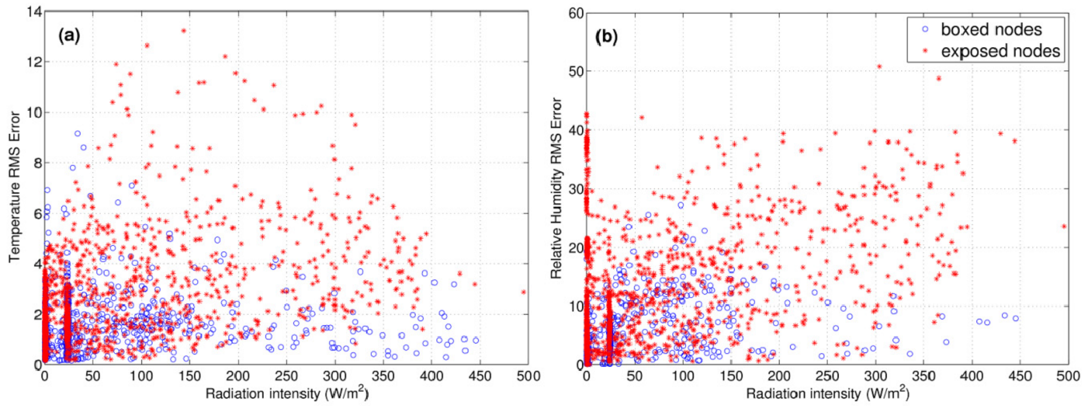

Figure 5. (a) Temperature and (b) relative humidity RMSEs versus radiation levels, in cases of "boxed" and "exposed" nodes.

In the 3rd experiment, in the case of temperature measurements, "shaded" nodes seemed to perform even better than "boxed" nodes, as the deviations between the two nodes measurements were smaller and practically not influenced by radiation intensity levels (Figure 6a). During night hours in particular, "boxed" sensors performed rather poorly as far as their spreading is concerned. Similarly, the corresponding RMSEs of the "shaded" sensor nodes were slightly smaller than those of the "boxed" sensors (Figure 6b). In the case of relative humidity measurements, the standard deviations of the values showed that "shaded" nodes were influenced by solar radiation intensity, while "boxed" sensor nodes were kept rather uninfluenced. However, the RMSEs of the groups of sensors showed, as in the case of temperature measurements, that "shaded" sensor nodes were slightly more accurate in general than "boxed" nodes. The accuracy and reliability of measurements provided by those "shaded" nodes make the development of some compensation algorithm that would take radiation intensity levels into account, rather unnecessary.

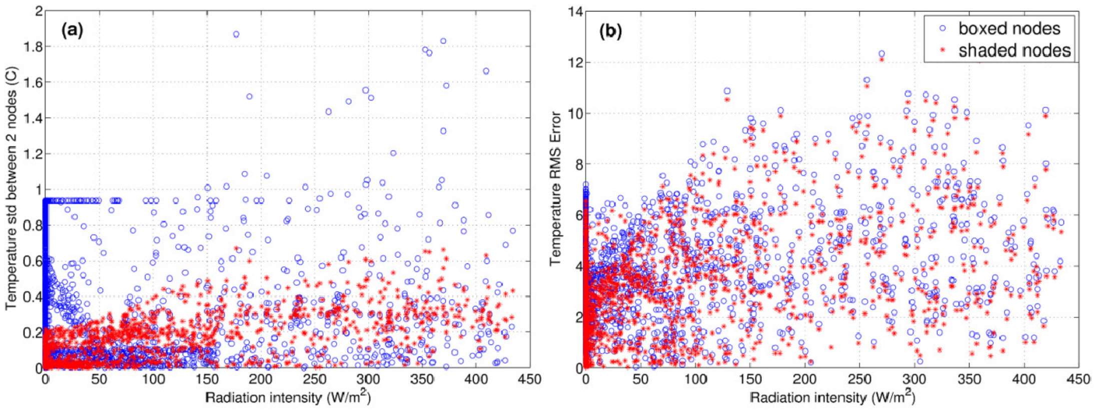

Figure 6. (a) Temperature standard deviations between 2 sensor nodes and (b) temperature RMSEs, versus radiation levels, in cases of "boxed" and "shaded" nodes.

CONCLUSIONS

A prototype WSN was developed and installed inside a greenhouse in order to investigate the effects of actual greenhouse conditions to the operation reliability of the sensor network measurements. It was shown that temperature and relative humidity measurements reliability is drastically influenced by solar radiation intensity, making the protection of wireless sensor nodes from high levels of solar radiation absolutely necessary. However, experiments with different levels of shading protection showed that drastic measures are not necessary, as simple shading of the wireless sensor nodes under some metallic surface is sufficient in providing protection that leads to accurate and stable measurements, even more reliable that those provided by nodes enclosed in highly protective, ventilated boxes.

As future work, the proposed WSN setup will be installed in a commercial greenhouse facility in order to accurately identify spatial climatic fluctuations of the greenhouse microenvironment and use that knowledge for the achievement of precise environmental control that would lead to energy conservation and more uniform quantity and quality of produce.

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