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### REFRIGERATED FRUIT STORAGE MONITORING USING RFID AND WSN

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**Abstract** Every day, millions of tons of temperature sensitive goods are produced, transported, stored or distributed worldwide. For all these products the control of temperature is essential. The quality of these products might change rapidly, when inadequate temperature and relative humidity conditions happened. It is estimated that 300 million tons of produce are wasted annually through deficient refrigeration worldwide. Quality control and monitoring of goods during the cold chain is an increasing concern for producers, suppliers, logistic decision makers and consumers. In this framework, Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSN) are entering in a new phase. RFID was developed for identification; however, recent developments in RFID hardware outfitted with sensors extend its range of application. Wireless sensor nodes, known as motes, enable environment sensing together with data processing. In this paper we present the results of a set of studies performed in 3 commercial wholesale chambers of 1848 m<sup>3</sup>, with different set points and products. Up to 90 semi-passive RFID temperature loggers were installed simultaneously together with 7 motes, during one week in each chamber. The motes host a variety of sensors: temperature, relative humidity, light intensity, barometric pressure and two-axis accelerometer. 3D temperature mapping charts were obtained and also the psychrometric data model from ASABE was implemented for the calculation of enthalpy changes and the absolute water content of air. Thus it was possible to estimate energy consumption, water loss from the products and detect condensation over the commodities.

**Keywords:** cold chain, logistics, postharvest, wireless sensor networks, RFID.

**INTRODUCTION** Every day, millions of tons of temperature sensitive goods are produced, transported, stored or distributed worldwide. For all these products the control of temperature is essential. The term “cold chain” describes the series of interdependent equipment and processes employed to ensure the temperature preservation of perishables and other temperature-controlled products from the production to the consumption end in a safe, wholesome, and good quality state (Zhang, 2007). Thus, the major challenge is to ensure a continuous ‘cold chain’ from producer to consumer in order to guaranty prime condition of goods (Ruiz-Garcia et al., 2007). These products can be perishable items like

fruit, vegetables, flowers, fish, meat and dairy products or medical products like drugs, blood, vaccines, organs, plasma and tissues. All of them can have their properties affected by temperature changes.

**Problematic** The quality of these products might can change rapidly, when inadequate temperature and relative humidity conditions during transport and storage. Temperature variations can occur in warehousing, handling and transportation. Inadequate temperature is second on the list of factors causing foodborne illness, surpassed only by the initial microflora present in foods (Sánchez López et al., 2008). It is estimated that 300 million tons of produce are wasted annually through deficient refrigeration worldwide (IIR/UNEP, 2002). Thus, studying and analyzing temperature gradients inside refrigeration rooms, containers and trucks is a primary concern of the industry. Any temperature disturbance can undermine the efforts of the whole chain (Meenke, 2006).

It is not easy to maintain appropriate conditions over the whole chain, negligence or mishandling in the logistic of perishable food products is very common, including goods poorly or excessive cooled. Roy et al. (2006) analyzed the supply of fresh tomato in Japan and quantified product losses of 5% during transportation and distribution (Roy et al., 2006). Tanner and Amos (2003a and 2003b) studied thermal variations during long distance transportation of fruits from New Zealand to Europe. The results showed that the products were out of the set-point more than 30% of the time, with a significant variability both spatially across the width of the container as well as temporally along the trip. In those experiments monitoring was achieved by means of the installation of hundreds of wired sensors in a single container, which makes this system architecture commercially unfeasible (Tanner et al., 2003).

Specialized WSN (Wireless Sensor Network) monitoring devices promise to revolutionize the shipping and handling of a wide range of perishable products giving suppliers and distributors continuous and accurate readings throughout the distribution process. In this framework, ZigBee was developed as a very promising protocol for WSN due to its low energy consumption and advanced network capabilities. Its potential for monitoring was proposed by several authors but there were no real experimentation, only theoretical approaches (Qingshan et al., 2004; Jedermann et al., 2006; Wang, 2006). For this reason, in this work real experimentation was a priority with the aim of exploring the limits of this technology. ZigBee motes (transmitters) have been validated for their use under cooling conditions in warehouses, studying the behavior of the motes in fruit chambers. Battery life was clearly affected under cooling conditions, with the duration at 0°C being half that at 20°C (Ruiz-Garcia, 2008; Ruiz-Garcia et al., 2008).

Apart from temperature, water loss is one of the main causes of deterioration that reduces the marketability of fresh fruits and vegetables. Transpiration is the loss of moisture from living tissues. Most weight loss of stored fruit is caused by this process. Relative humidity (RH), temperature (T) of the product, temperature of the surrounding atmosphere, and air velocity all affect the amount of water lost from perishable food products. Free water or condensation is also a problem as it encourages microbial infection and growth, and it can also reduce the strength of packaging materials (Shamaila, 2005).

**OBJECTIVES** The aim of this work is to improve the refrigerated storage of perishable food products through the implementation of wireless sensing technologies. Focusing on

the analyses of the performance of semi-passive RFID loggers and WSN motes in order to enable an economical solution for the spatial profiling of refrigerated chambers with a high number of loggers.

## MATERIALS AND METHODS

**Refrigerate chambers** Experiments were performed in three commercial wholesale refrigerated stores, numbered 11, 29 and 40. Each of which has a volume at of 1848 m<sup>3</sup>, 26 x 6 x 12 m, with an on/off glycol cooling system and insulated walls built of foam sandwiched between two layers of corrugated plate (total wall thickness is 0.16 m). The set points experimentation time were different in each one (see table 1). Each chamber has a common pre-chamber space where a devoted sensor is placed. Therefore, three different ambient conditions occur: outdoor, pre-chamer and inside chamber with well known set point (see Table 1).

**Table 1.** Experimental conditions.

Cold store number	Set point (°C)	Experimentation time (days)	Dates
11	8	13	7 <sup>th</sup> - 19 <sup>th</sup> July
29	7	8	20 <sup>th</sup> - 27 <sup>th</sup> July
40	14	4	28 <sup>th</sup> - 31 <sup>st</sup> July

**ZigBee motes** Two ZigBee/IEEE 802.15.4 motes (transmitters) and one base station (receiver) were used. One mote was installed outside the chamber, close to the door and the other one inside, at the other side of the wall. Sample rate was set to 180s.

These motes were manufactured by Crossbow® and they have a microcontroller board (IRIS) together with an independent transducer board (MTS400) attached by means of a 52 pin connector. Its processor & radio platform is a XM2110CA, based on the Atmel ATmega1281. The RF power was configured to 3 dBm (three times over previous MICA Motes). Power was supplied by two AA lithium batteries.

The MTS400 board hosts a variety of sensors: temperature and relative humidity (Sensirion SHT), barometric pressure and temperature (Intersema MS5534B), light intensity (TAOS TSL2550D) and a two-axis accelerometer (ADXL202JE). A laptop computer is used as the receiver, and communicates with the nodes through a Micaz mounted on the MIB520 ZigBee/USB gateway board; this device also provides a USB programming interface. In this study only the data from Sensirion and Intersema is used.

The Sensirion SHT is a single-chip relative humidity and temperature multi-sensor module that delivers a calibrated digital output. Each SHT is individually calibrated in a precision humidity chamber. The calibration coefficients are programmed into the OTP (One Time Programmable) memory. These coefficients are used internally during measurements to calibrate the signals from the sensors.

For temperatures significantly different from 25°C, and according to the manufacturer recommends performing humidity and temperature compensation, using equations 1 and 2.

$$RH_{linear} = (-4) + 0.0405 * SO_{RH} + (-2.8 * 10^{-6}) * SO_{RH}^2 \quad (1)$$

$SO_{RH}$  = Sensor Output Relative Humidity

$$RH_{true} = (T^{\circ}C - 25) * (0.01 + 0.00008 * SO_{RH}) + RH_{linear} \quad (2)$$

The MS5534B is a SMD-hybrid device including a piezoresistive pressure sensor and an ADC-Interface IC. It provides a 16 Bit data word from a pressure and temperature (-40 to +125°C) dependent voltage. Additionally the module contains 6 readable coefficients for a highly accurate software calibration of the sensor. MS5534B is a low power, low voltage device with automatic power down (ON/OFF) switching. A 3-wire interface is used for all communications with a microcontroller. Sensor packaging options are plastic or metal cap.

**Semi-passive RFID tags.** Up to 90 RFID semi-passive loggers were installed in each chamber. The tags were manufactured by Sealed Air. Each tag operates in the band of 13.56 MHz (ISO 15693-3 compliant), has the size of a credit card, is accurate to within  $\pm 0.5^{\circ}C$  and can store 702 temperature measurements.

**Data analysis** A specialized Matlab program has been developed for assessing the percentage of lost packets (%) in transmission, by means of computing the number of multiple sending failures for a given sample rate (SR). A multiple failure of m messages occurs whenever the elapsed time between two messages lies between  $1.5 \times m \times SR$  and  $2.5 \times m \times SR$ . For example, with a sample rate of 11 s, a single failure (m=1) occurs whenever the time period between consecutives packets is longer than 16.5 s ( $1.5 \times 1 \times 11$ ) and shorter than 27.5 s ( $2.5 \times 1 \times 11$ ). The total number of lost packets is computed based on the frequency of each failure type. Accordingly, the total percentage of lost packets is calculated as the ratio between the total number of lost packets and the number of sent packets.

The standard error (SE) associated to the ratio of lost packets is computed based on a binomial distribution as expressed in equation 3, where n is the total number of packets sent, and p is the ratio of lost packets in the experiment.

$$SE = \sqrt{\frac{p(1-p)}{n}} \quad (3)$$

A second devoted Matlab code was used for plotting 3D temperature gradients. This program makes use of linear spatial interpolation in order to obtain 3D representations of normalized temperatures and variances inside the chambers. Due to the significant variation of external conditions in the Spanish summer, temperature analysis make use of a normalized temperature difference ( $\Delta T_n$ ), which is computed with respect to the set

point and to the outside temperatures (see equation 4). This value gives a normalized measure with respect to the varying ambient conditions of the experiments.

$$\Delta T_n = \frac{T_m - T_s}{T_e - T_s} \quad (4)$$

where  $\Delta T_n$  (dimensionless) stands for the normalized temperature difference,  $T_m$  is the average temperature value (°C) of each RFID logger,  $T_s$  is the temperature set point value (°C), and  $T_e$  refers to the average outside temperature (°C).

Finally, a 3D plot of indoor temperature variance with regard to outdoor temperature variance is performed in order to represent the indoor temperature variability corrected with regard to changes in ambient experimental conditions (see equation 5). The complete set of data is included for each experiment.

$$V_n = \frac{V_i}{V_e} \quad (5)$$

where  $V_n$  is the normalized indoor variance for experiment,  $V_i$  is the indoor temperature variance of each logger, and  $V_e$  is the outside variance.

**Psychrometric data** The ASAE D271.2, defined in April 1979 and reviewed in 2006, is used for computing the psychrometric properties of air (ASABE, 2006). Equations 6, 7, 8, 9 and Table 2 enable the calculation of all psychrometric data of air whenever two independent psychrometric properties of an air-water vapor mixture are known in addition to the atmospheric pressure.

$$P_s = e^{31.9602 - \frac{6270.3605}{T} - 0.46057 \cdot \ln T} \quad (6)$$

$$-255.38 \text{ K} \leq T \leq 273.16 \text{ K}$$

$$P_s = R * e^{\frac{A+B*T+C*T^2+D*T^3+E*T^4}{F*T-G*T^2}} \quad (7)$$

$$273.16 \text{ K} \leq T \leq 533.16 \text{ K}$$

$T$ =Temperature (K),  $P_s$ = Saturation vapour pressure (Pa) (ASABE, 2006).

$$P_v = P_s \frac{RH}{100} \quad (8)$$

$P_v$ = Vapor pressure (Pa) (ASABE, 2006).

$$H = \frac{0.6219 * P_v}{P_{atm} - P_v} \quad (9)$$

$H$ =Absolute humidity (g/kg dry air),  $P_{atm}$ = Atmospheric pressure (Pa) (ASABE, 2006).

Table 2. Coefficients used to compute the psychrometric data, according to equation 5 (ASABE, 2006).

R=22,105,649.25	D=0.12558x10-3
A=-27,405.526	E=-0.48502x10-7
B=97.5413	F=4.34903
C=-0.146244	G=0.39381x10-2

## RESULTS

**Percentage of lost packets** The 3 dBm of RF power used by the motes were enough to enable sending data outside the chamber. More than 98% of the packets sent were able to cross over the walls (see Table 3). Only 1.25% of signals were lost in the worst case (chamber 11). It is important to state that in previous experiments using motes with 1dBm of RF power almost all the packets were lost (Ruiz-Garcia, 2008).

Table 3. Percentage of data lost packets and standard error during the experiments.

Cold store number	Mote inside (data)	Mote outside (data)
11	0.26±0.01 (6117)	1.25±0.01 (6007)
29	0.24±0.02 (3244)	0.89±0.02 (3223)
40	0.21±0.02 (1846)	0.70±0.02 (1826)

**3D plots** Figures 1 and 2 show a summary of 3D views corresponding to temperature behavior for chambers 11 and 29. Both the  $\Delta T_n$  and normalized temperature variance are represented. In both cases mean temperatures were close to the set point ( $0 \Delta T_n$ ). The highest differences were registered by the sensors located in the ceiling where the air stream from the evaporators blows. The temperature in chamber 11 was less homogeneous than in chamber 29, as indicated by higher normalized variance, which can be addressed to the existence of an intermediate wall that divides the refrigerated chamber in two zones.

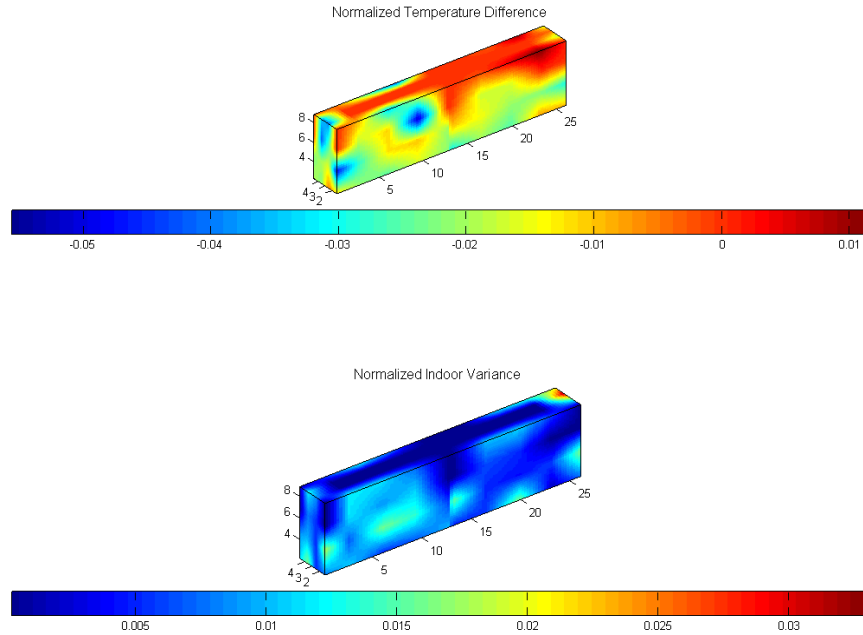


Figure 1. 3D plot of Normalized Temperature Difference and Indoor Variance in chamber 11.

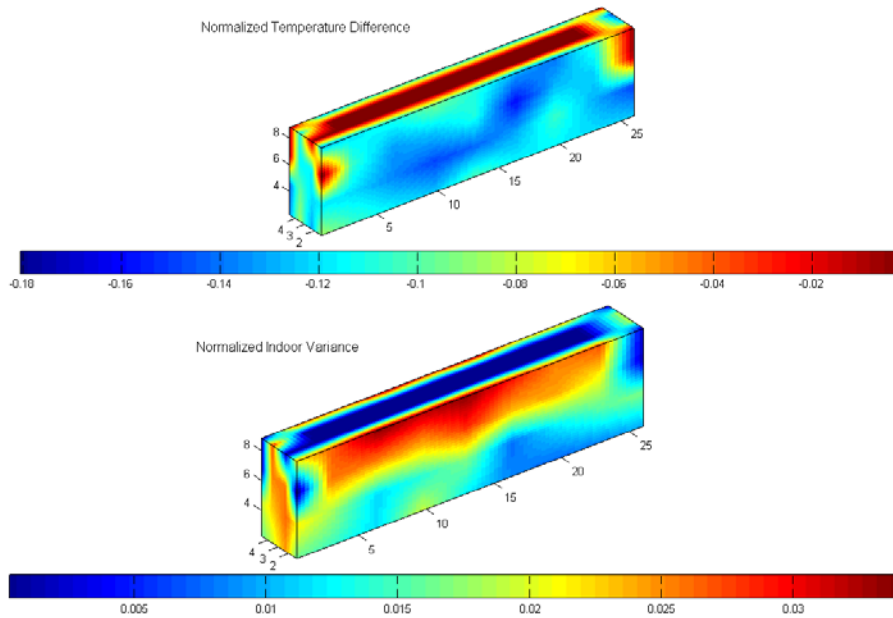


Figure 2. 3D plot of Normalized Temperature Difference and Indoor Variance in chamber 29.

**Psychrometry** he absolute humidity of the air inside the chambers was calculated, based on the ASAE standard D271.2 (1979) (ASABE, 2006), using the data recorded during experiments.

Psychrometric charts for two chambers (numbers 29 and 40) are included in Figure 3 and 4, which illustrate the evolution of air absolute humidity ( $H$ , kg of water/ kg of dry air) related to the  $T$  ( $^{\circ}\text{C}$ ). The blue cloud corresponds to the mote inside the chamber while the red one refers to the mote located outside (pre-chamber). Door openings created an increment in  $T$  ( $^{\circ}\text{C}$ ) and  $H$  (kg of water/ kg of dry air), which then returns to normal again once the door is closed. During the rest of the time, it is also possible to detect the interaction between air properties and the product; with the cycles of cooling, variations in the absolute humidity can be estimated: condensation over the products (as loss of absolute humidity), or water evaporation (as an increase in absolute air humidity).

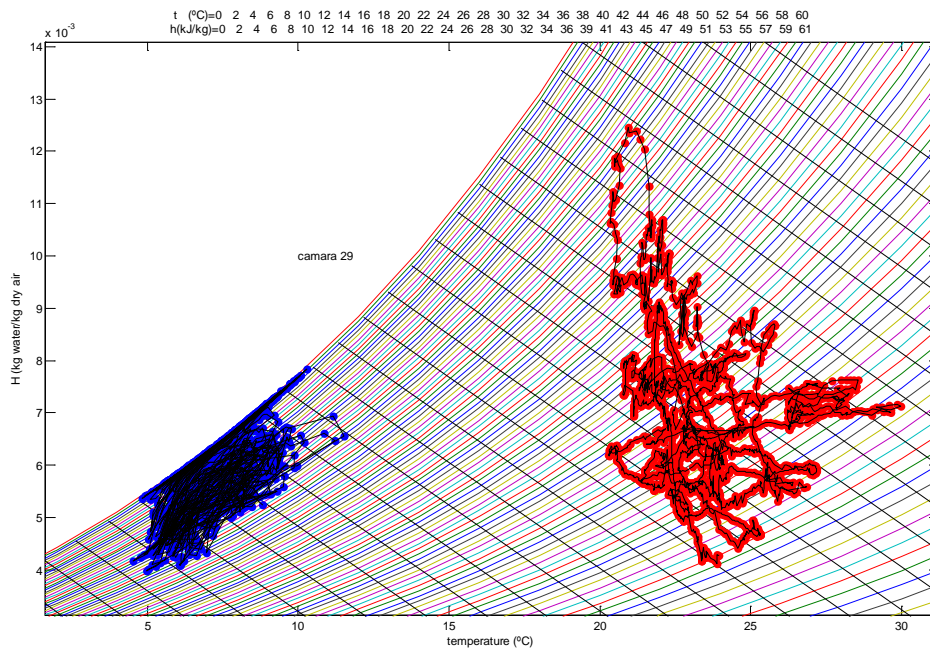


Figure 3. Psychrometric chart in chamber 29. Color lines indicate relative humidity between 100% and 20%

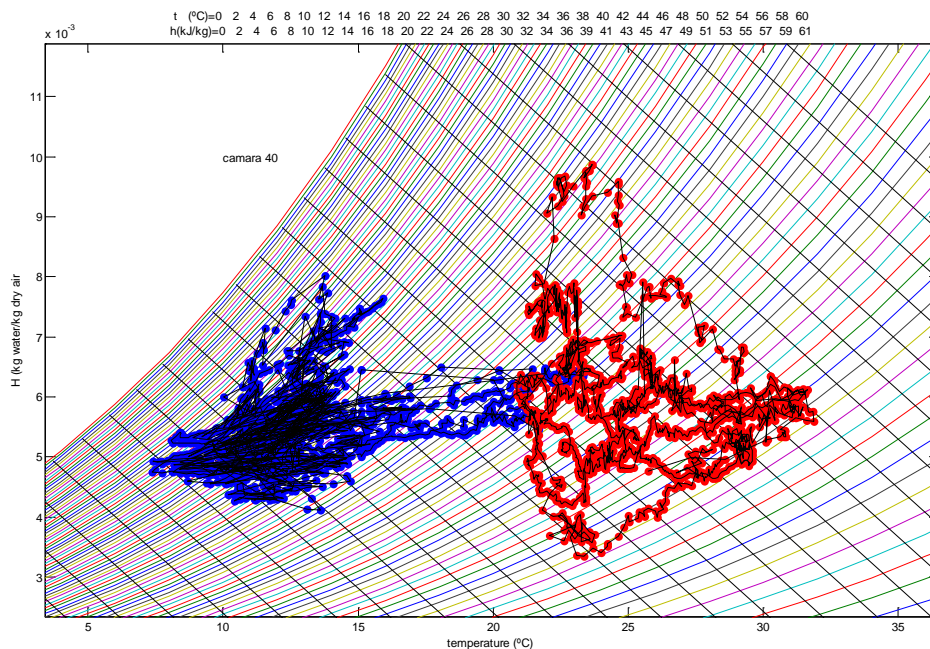


Figure 4. Psychrometric chart in chamber 40. Color lines indicate relative humidity between 100% and 20%

Figure 3 and 4 confirm the differences in temperature set-point since pre-chamber and inside temperature are more separated for camber 29 (7 °C) than for chamber 40 (14 °C). Moreover two different psychrometric paths can be addressed (a vertical and a horizontal one). The horizontal refers to air heating either inside or in the pre-chamber when such

locations are closed, while the vertical one could correspond to air humidity increase or dehydration.

**CONCLUSIONS** The last generation of commercial ZigBee motes, that have three times the RF power (3dBm) of the previous ones (1dBm), are able to cross over standard isolation in cold storage facilities.

The use of psychrometric equation provides very valuable information regarding air fluxes and water transport phenomena from the product to the air. Using two sensors of just one single mote is possible to obtain such information in real time.

The relative low cost of the RFID loggers allows dense implementations that provide accurate information about temperature gradients inside the chambers. The limitation of these loggers is the reading range and sensing capabilities, and so there is a need for improving the range of sensing technologies such as volatiles.

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