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b+WSN: Smart Beehive for Agriculture, Environmental, and Honey Bee Health Monitoring - Preliminary Results and Analysis

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***Abstract*—In recent years, various United Nations reports have stressed the growing constraint of food supply for Earth′s growing human population. Honey bees are a vital part of the food chain as the most important pollinator insect for a wide range of crops. It is clear that protecting the population of honey bees worldwide, as well as enabling them to maximise their productivity, is an important concern. The work described in this paper utilised heterogeneous wireless sensor networks technologies to gather data unobtrusively from a beehive, describing the conditions and activity of the honey bee colony. A wide range of sensors were deployed for monitoring the multi-dimensional conditions within a living beehive (including oxygen, carbon dioxide, pollutant levels, temperature, and humidity). Meteorological and environmental conditions outside the hive were also monitored throughout the deployment. The data were then analysed from a biological perspective to provide insights into honey bee behaviour and health. This led to the development of an algorithm for automatically determining the status of the bee colony. Analysis was also undertaken from a meteorological perspective, which led to the development of an algorithm for predicting short term external weather conditions (rain) based on the conditions observed within the hive. The meteorological conditions were seen to have an impact on the data provided by biological sensors (bees) and physical sensors. This can be exploited to improve the accuracy of local weather prediction. Applications of this algorithm include agricultural and environmental monitoring for accurate short term forecasts for the area local to the beehive.**

***Index Terms*—Honey Bee Monitoring; Honey Bee Sensors; Wireless Sensor Networks; Embedded Systems; Environmental Monitoring; Biological and Physical Sensors; Weather Prediction**

I. Introduction

Humans and honey bees have had an important relationship from the beginning of civilisation, with records of keeping hives for agriculture (honey and wax collection) dating as far back as 2400 BC [1]. In modern times the Western honey bee (*Apis mellifera*) plays a role in a range of human activities, including nutrition, medicine, agriculture, and social studies. The most vital activity of the honey bee for humans is pollination, with the EU parliament noting in 2008 (resolution T6-0579/2008) that 79% of human food depends on honey bee pollination. As the global human population grows, in order to secure food supplies, the amount of pollinator dependant crops will increase dramatically. In [2] it was found that the volume of pollination dependant crops has grown 300% in the last 50 years. To protect the worldwide food supply, as well as agriculture-dependant economies, it is clear that honey bee populations need to be maintained in an optimal state of health and afforded opportunities to grow.

Wireless Sensor Networks (WSN) are made up of embedded devices with sensing, computing, and communication abilities. They form a fundamental building block of the "Internet of Things" (IoT) concept. WSN has found applications in every aspect of human life, including healthcare, structural monitoring, and medicine [3][4][5]; this flexibility has increased the popularity of WSN research in both industry and academia.

The work described in this paper utilised heterogeneous WSN to gather data unobtrusively from a beehive and analyse the data to gather information about the conditions and activity of the honey bee colony. The analysis of these data provided a unique picture of the beehive conditions at times when traditional beekeeping methods are not possible (night-time, poor weather, etc.). Innovative techniques were then used to estimate conditions outside the hive and predict local weather. A typical bee colony costs ˜€ 200, and so the impact of improved colony monitoring for an individual beekeeper is significant. On a global scale the value of pollination dependant crops is estimated at € 155 billion.

While many bee monitoring systems can be found in literature [6][7][8], it is clear that the interdisciplinary analysis of beehive data is in its infancy. In this paper the data have been analysed from biological, environmental, meteorological, and engineering perspectives. This leads to an expansion of the concept of a classical WSN, by utilising the bees as sensors

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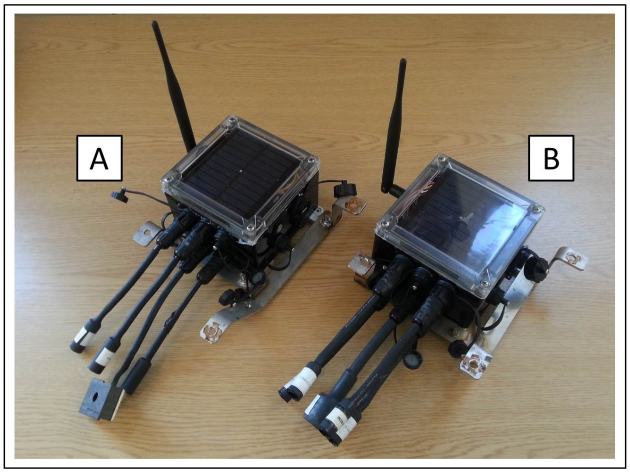

Fig. 1. Developed Sensor Nodes

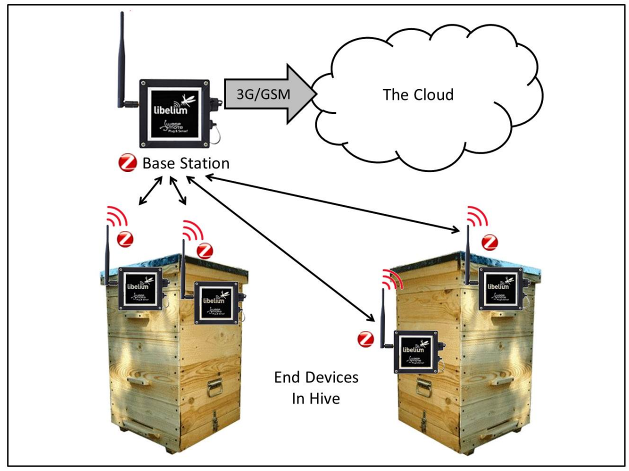

Fig. 2. Network transfers data from the hive to the cloud

and weather predictors as part of the network. Unlike other systems using bees as sensors [8], which physically attach sensors to individual bees, in this paper the bees are not modified and are allowed to perform their activities as normal.

This system can be used, with the bees acting as sensors, to provide feedback and prediction for the agriculture sector, which relies on accurate short term weather prediction and notification (covering an area of up to 50 sq. km - the area covered by the bees in a hive [9]). This would be of particular importance to economies such as Ireland where agriculture is primarily grass-based (including grass-based beef and dairy production) [10]. Such agricultural activities can be strongly influenced by weather changes, making accurate forecasting vital to production. There are strict environmental protection requirements relating to weather and common farming practices, including spreading of slurry and fertiliser. Identifying incoming weather is also crucial for other farming activities, including harvesting maximum amounts of silage, and preventing disease spread (blight, foot and mouth disease, etc.).

The contributions of this paper are: synchronised, multi-source, data collection relating to honey bee activity and weather; interdisciplinary analysis of data; and, using honey bees as sensors to extend the concept of a traditional WSN.

This paper is organised as follows: sction 2 describes recent work in the area of automated bee data collection and shows the motivation for the design choices. Section 3 gives an overview of the system prototype. Section 4 describes the deployment and results. Section 5 presents the analysis of the collected data and outlines the developed signal processing algorithms. Section 6 concludes the paper and is followed by a description of future plans for the project.

II. Related Work, Background & Motivation

Odoux et al. (2014) [6] proposed a method for long term monitoring of honey bee colonies, aiming to assess the effect of climate and human activities on hived bees. The approach by Odoux et al. (2014) required sampling twice per month, which provided far fewer data than the system described in this paper. They used invasive methods which disturb the colony, causing damage, and occasionally causing the colony to fail. The system described in this paper does not require the hive to be opened for readings, which makes it much less invasive.

Phillips et al. (2014) described a system in [7] where WSN were used to predict a beehive state known as "swarming", using temperature sensors. The system they proposed is only effective in hot climates, and the apparatus interfered with the beekeeper's access to the hive. The b+WSN system can collect valid data in any weather conditions, and does not prevent beekeeper activities which are critical for hive maintenance. Other systems, which are commercially available, focus on individual sensors, are battery powered, and are not 3G/GSM enabled for remote deployments [11][12].

The critical in-hive parameters which may indicate the status of the honey bee colony were identified as: temperature, humidity, Carbon Dioxide (CO_2) levels, and Oxygen (O_2) levels [13][14]. These are known to vary in response to one or more of these scenarios: the number of honey bees in the hive, the health of the colony, and the external weather.

The goal of the design outlined in this paper is to gain knowledge of the conditions within the hive, and use this knowledge to inform the beekeeper with the aim of maintaining a healthy hive through the use of heterogeneous wireless sensor networks and mobile technologies.

III. System Design

An in-depth description of the apparatus used in this experiment can be found in [15]. The Libelium "Waspmote" v 1.2 platform was selected to develop the beehive monitoring system. This platform uses an ATmega1281 microcontroller, and employs a modular architecture, supporting many sensors and radios. Low power sleep modes (0.7 μA) with duty cycling and energy harvesting allow for an extended lifetime.

Two in-hive sensor nodes were developed using this platform - a hive conditions node (max. ON current: 235mA at 3.3V-4.2V) and a gas level detection node (max. ON

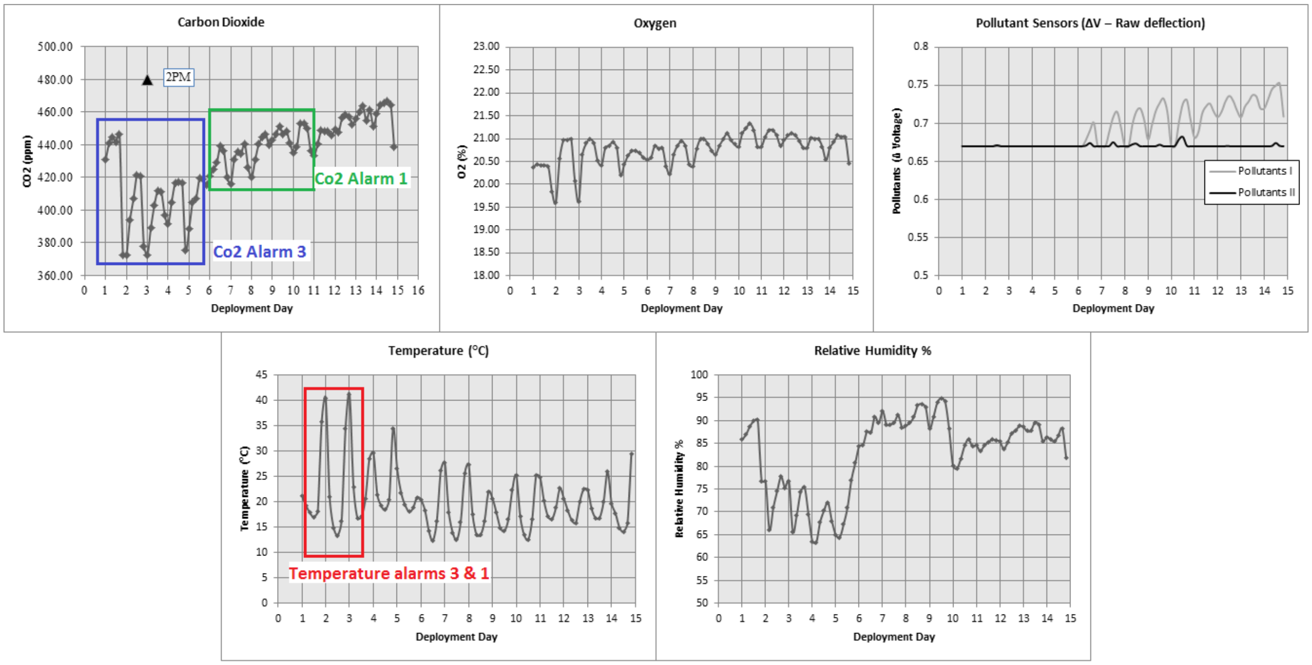

Fig. 3. Data collected over initial 14 days of deployment from 29/06/2014

current: 406mA at 3.3V-4.2V). The sensor combinations were selected based on the important parameters outlined above. Both of these nodes incorporated an XBee Series 2 Zigbee radio and a 205mA solar panel for energy harvesting. The general hive conditions sensor had 3 sensors: particle dust (GP2Y1010AU0F), humidity (808H5V5), and temperature (MCP9700A). This node also utilised the platform's built-in 3-axis accelerometer (LIS331DLH). The gas sensors were: molecular oxygen (O_2) SK-25; carbon dioxide (CO_2) TGS4161; nitrogen dioxide (NO_2) MiCS-2710; and two air contaminants TGS2600 and TGS2602 which sense gases including ethanol (CH_3CH_2OH), hydrogen sulphide (H_2S), and methane (CH_4). A base station (max. ON current: 375mA at 3.3V-4.2V) for collecting the data was developed. It incorporated an XBee Series 2 Zigbee radio and a GSM/GPRS/3G module. This node acted as the "bridge" between the Zigbee and 3G networks. It included a larger 520mA solar panel for increased energy harvesting due to multi-radio activity.

Fig. 4. Final smart hive at deployment site

The network structure can be seen in Fig. 2. Each in-hive device collected data several times per day. Once per 24 hours the Zigbee network synchronised, and end devices sent 24 hours of data to the base. The base station uploaded the data via 3G/GSM to a remote server. All data were time stamped as they were sampled, and were stored locally on SD cards as they passed through the network to minimise data loss in case of network/hardware failure. Each 24 hour cycle produced ~4kB of data, the storage on end devices and base station (2GB SD cards) are able to store over 1000 years of data.

The prototype of the system can be seen in Fig. 4. The sensor nodes were embedded into the hive roof, where the probes could effectively detect the hive conditions. The solar panels and antennae were extruded through the roof to allow energy collection and effective networking. This system allowed for effective operation, without preventing the beekeeper's activities in maintaining the hive and colony.

IV. Experimental Results

The first deployment of the prototype beehive monitoring system took place in Lyre, Co. Cork, Ireland (Fig. 6 [16]) on 29/06/2014 and continued until 13/07/2014. The prototype was then adjusted and redeployed from 11/08/2014 onwards. This is the site of an established apiary which had a healthy bee colony available for monitoring. The weather conditions were recorded daily throughout the deployment and can be seen in Fig. 8 and Fig. 11. This allowed the different conditions within the hive due to changing weather to be observed.

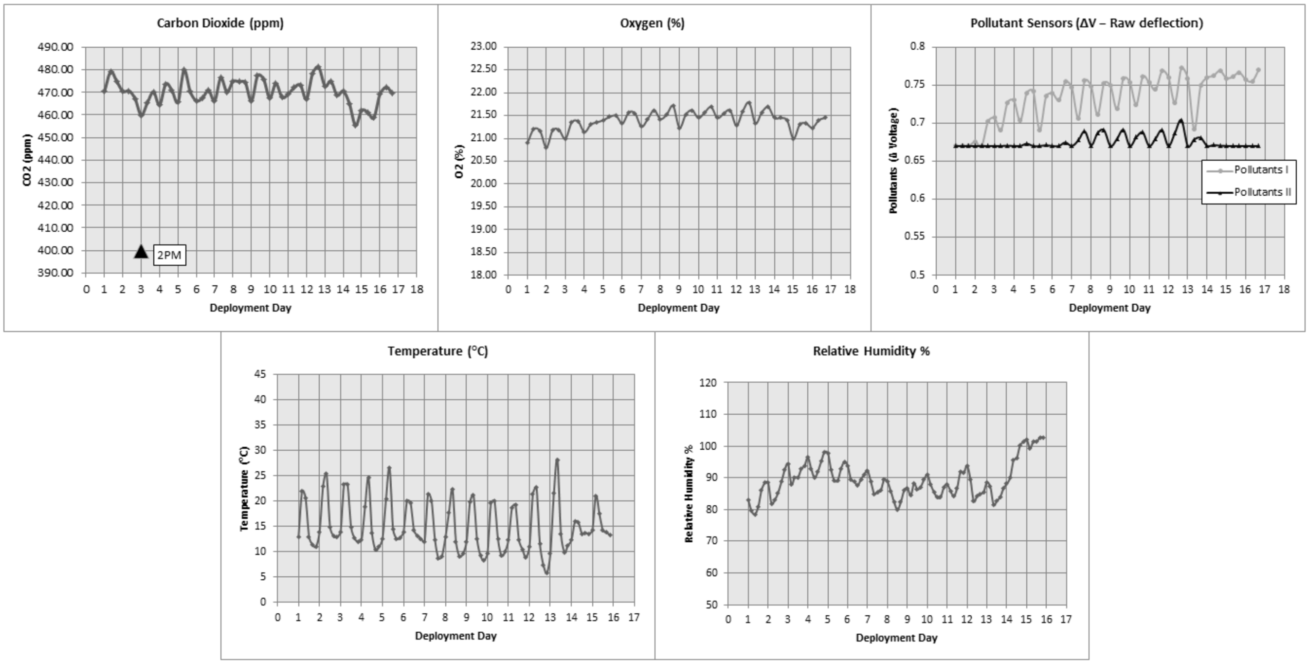

Fig. 5. Data collected over 16 days in adjusted deployment from 11/08/2014

Weather data were obtained from the Irish national meteorological service Met Éireann [17]. The temperature, wind speed, atmospheric pressure, and rainfall were recorded from the nearest automatic weather station at Moorepark, Co. Cork, Ireland (39km from deployment); the sunlight data were recorded from Cork Airport, Co. Cork (40 km from deployment), Ireland. Rainfall data were also collected manually (with a 7am to 7am window, rather than 12am-12am of automatic station) at the site of the apiary by the beekeeper.

Fig. 3 and Fig. 8 show the results collected from the first two weeks of the deployment, during which all sensor nodes were sampled 6 times per day. The sampling rate was then adjusted to sample general conditions 6 times per day, and gas levels 3 times per day from 11/08/2014 to the 27/08/2014. Results from the adjusted deployment can be seen in Fig. 5 and Fig. 8.

These data are presented as graphs, with time on the X-axis, the vertical gridlines mark the 2pm point in each 24 hour period, allowing the diurnal pattern in almost every dataset to be seen clearly. In the first set of results (June-July deployment) large fluctuations in temperature and carbon dioxide were observed initially, with both parameters stabilising towards the end of the deployment. Oxygen in the first deployment was found to remain steady over the 14 days, while pollutant levels and humidity varied. In the second deployment the carbon dioxide, temperature, and oxygen readings were quite constant over the duration of the readings. The pollutant levels were seen to grow slowly as the deployment progressed.

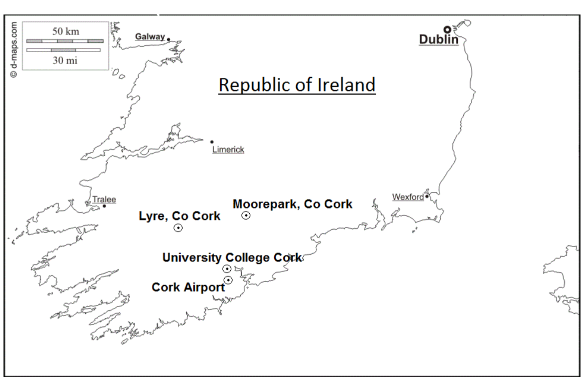

Fig. 6. Map of deployment site, weather stations, and server location

V. Analysis & Algorithm Implementation

The results gathered from both deployments were analysed from two perspectives, firstly from a biology and beekeeping perspective, assessing the condition of the beehive and colony. Secondly they were analysed, along with the collected weather data with a view to exploring their meteorological and environmental implications. Future deployments of multiple hives will be used to validate and improve the results of this analysis.

A. Biological & Beekeeping Analysis

The first observation that the temperature of the hive roof cavity typically remained within a steady range of min 9-12 °C, max. 20-30°C, with a diurnal fluctuation. These temperatures were achieved regardless of external weather conditions, which indicate that the activities of the bees, during day and night, maintained internal temperatures that were higher than those of the external environment. It was observed that temperatures varied more during the day than at night. This is due to the majority of the adult honey bees leaving during the day to forage, thus reducing the number of bees

procedure TEMP($T0, ...T6$) ▷ Temperature over 24 hours
  $Tmax \leftarrow max$(T0,...T6)
  $Tmin \leftarrow min$(T0,...T6)
  $deltaT \leftarrow Tmax - Tmin$
  if $Tmin < 7$ **then**
    $alarm1$ ▷ Hive is too cold
  else if $Tmax > 37$ **then**
    $alarm2$ ▷ Hive is too hot
  end if
  if $deltaT < 20$ **then**
    $alarm3$ ▷ Temperature is fluctuating - check hive
  end if
  sleep ▷ Wait for another sample
end procedure

Fig. 7. Temperature Algorithm

available to maintain more stable and higher temperatures. Cyclical temperature fluctuations throughout the day were seen to be typical of a normal, healthy hive. Departure from this behaviour should indicate decreased honey bee numbers. An algorithm was proposed to automatically detect these factors is shown in Fig. 7. This was validated using deployment data and produced accurate swarming alarms shown in Fig. 3.

The humidity within the hive appeared to respond to the external meteorological conditions. During both deployments the humidity rose noticeably on days when high levels of rainfall were recorded. At the end of the second dataset, with rainfall of <17mm per day, extreme humidity to the point of condensation within the roof space was recorded.

At the surface of Earth, atmospheric concentrations of CO_2 are normally measured at approximately 400ppm and it is clear that respiration by the bees in the hive raised the CO_2 concentration to levels of between 400 and 500ppm with a diurnal cycle of lower levels during daytime though these differences tended to become reduced as the time increased. In the June-July experiment the CO_2 levels were initially similar to ambient conditions (which were also recorded in an empty adjacent hive) with a diurnal pattern. They rose until they were consistently measured at 460 - 480ppm and in the July - Aug experiment they were remarkably constant at this 460 - 500 ppm level. It is noteworthy that while oxygen levels continuously matched those of the external environment, CO_2 built up in the hive. This suggests that the airflow at the top of the hive provided ambient O_2 while permitting CO_2 to build up to levels that were almost 20% above ambient. A swarming (half of the colony's population left to form a new hive) was observed prior to the first deployment, it is suggested that the low and fluctuating CO_2 levels at the start of the June-July deployment was due to having insufficient adult bees to maintain stable airflow conditions within the hive. In this way, observing the CO_2 levels within the hive can provide the end user with an indication of whether or not the beehive contains a full, stable colony. An algorithm to identify the status of the colony was proposed as shown in Fig. 9 this algorithm was also validated providing alarms shown in Fig. 3.

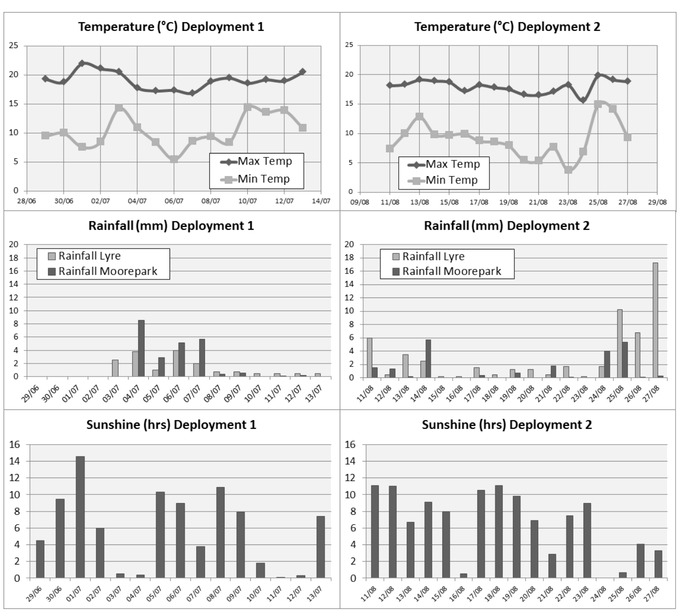

Fig. 8. Weather 29/06/2014 to 13/07/2014 and 11/08/2014 to 27/08/2014

procedure CO_2($C0, ...C4, T$) ▷ CO_2 over 24 hours and current temperature
  $Cavg \leftarrow average$(C0,...C4)
  $Cmax \leftarrow max$(C0,...C4)
  $Cmin \leftarrow min$(C0,...C4)
  $deltaC \leftarrow Cmax - Cmin$
  if $Cavg < 450$ AND $T > 7$ **then**
    $alarm1$ ▷ Potential illness or swarm
  else$Cavg < 450$ AND $T < 7$
    $alarm2$ ▷ Colony may be hibernating
  end if
  if $deltaC > 20$ **then**
    $alarm3$ ▷ CO_2 is fluctuating - check hive
  end if
  sleep ▷ Wait for another sample
end procedure

Fig. 9. Carbon Dioxide Algorithm

procedure RAIN($C0, C1, C2$) ▷ CO_2 at 2pm, 10pm, 6am
  $Yday \leftarrow C1 - C0$ ▷ If C1>C0 good day
  $Night \leftarrow C1 - C2$ ▷ If C2>C1, expect change
  if $Night >= Yday$ **then**
    $alarm1$ ▷ Predict bad weather today
  else
    $alarm2$ ▷ Predict good weather today
  end if
  sleep ▷ Wait 24 hours
end procedure

Fig. 10. Weather Prediction Algorithm

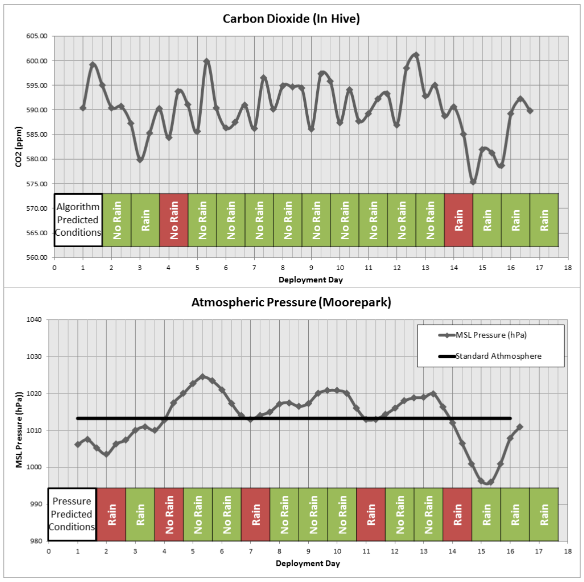

Fig. 11. Output of Weather Prediction Algorithm Compared to Prediction based on Atmospheric Pressure

The pattern observed in the pollutant sensors (nitrogen dioxide, and raw data from pollutant sensor I and II) is that initially low levels were detected, with the volume growing over time from that point. This suggests that removal of the roof ventilated the beehive of some pollutants, and the same gases then built up within the hive when the roof is in place.

B. Meteorological & Environmental Analysis

When the local meteorological data were analysed, it was observed that in-hive CO_2 levels varied in a similar manner to weather patterns, the correlation coefficient between the CO_2 levels in the hive and the atmospheric pressure (Moorepark) was found to be ˜0.6. Using this observation an algorithm was proposed to predict rain patterns local to the hive. This algorithm is outlined in Fig. 10; it was validated using the deployment data, the results are shown in Fig. 11. A green tag indicates a successful prediction; a red tag indicates the prediction was not correct. The algorithm predicted rain/no rain with 87% accuracy, compared with the 68% accuracy over the same period using the closest pressure data (Moorepark).

Another potential impact from weather or the environment is the hive being knocked over, either due to a gust of wind or an animal. This would require a beekeeper to visit the hive immediately so that the bees do not chill or get rained upon, which could be fatal. The final proposed alarm is triggered when the Z-axis (vertical) of the hive as measured by the accelerometer drops to less than 9.81m/s^2 (gravity of Earth).

VI. Conclusion

Two successful deployments of the b^+WSN system took place on a beehive. The results were analysed from biological, environmental, meteorological and engineering perspectives. Based on the biological analysis several algorithms were proposed to automatically detect important hive changes, and alert the beekeeper to potential colony threats. From the meteorological analysis a short term, local, weather prediction algorithm was proposed based on CO_2 levels within the hive. The proposed algorithms were verified by comparing the outputs from the deployments to observations from the beekeeper and official Irish weather records.

In the future, additional sensors for beehive monitoring will be deployed. This will include additional CO_2 and temperature sensors to provide a picture of how these key parameters change in different sections of the beehive. This step will also include developing dedicated beehive sensors measuring previously unobserved conditions. Another future step will include expanding the energy harvesting sources from solar power alone, to guarantee the longevity of deployments, even during overcast weather and the winter.

A second deployment of the monitoring system on an active beehive is planned for early 2015, which will include the described additional sensors. This will provide a larger window of data over which to validate signal processing techniques. It is also planned to implement this paper's signal processing techniques in-network, along with some machine learning algorithms, for automated condition analysis at the hive level.

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