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Development of an Heterogeneous Wireless Sensor Network for Instrumentation and Analysis of Beehives

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***Abstract*—Honey bees have held a critical role in agriculture and nutrition from the dawn of human civilisation. The most crucial role of the bee is pollination; the value of pollination dependant crops is estimated at €155 billion per year with honey bees identified as the most important pollinator insect. It is clear that honey bees are a vitally important part of the environment which cannot be allowed to fall into decline. The project outlined in this paper uses Wireless Sensor Network (WSN) technology to monitor a beehive colony and collect key information about activity/environment within a beehive as well as its surrounding area. This project uses low power WSN technologies, including novel sensing techniques, energy neutral operation, and multi-radio communications; together with cloud computing to monitor the behaviour within a beehive. The insights gained through this activity could reduce long term costs and improve the yield of beekeeping, as well as providing new scientific evidence for a range of honey bee health issues. WSN is an emerging modern technology, key to the novel concept of the Internet of Things (IoT). Comprised of embedded sensing, computing and wireless communication devices, they have found applications in nearly every aspect of daily life. Informed by biologists' hypotheses, this work used existing, commercially available WSN platforms together with custom built systems in an innovative application to monitor honey bee health and activity in order to better understand how to remotly monitor the health and behaviour of the bees. Heterogeneous sensors were deployed, monitoring the honey bees in the hive (temperature, CO2, pollutants etc.). Weather conditions throughout the deployment were recorded and a relationship between the hive conditions and external conditions was observed. A full solution is presented including a smart hive, communication, and data aggregation and visualisation tools. Future work will focus on improving the energy performance of the system, introducing a more specialised set of sensors, implementing a machine learning algorithm to extract meaning from the data without human supervision; and securing additional deployments of the system.**

Keywords*—*Wireless Sensor Networks; 3G mobile communication; Embedded systems; energy harvesting; Zigbee.

I. Introduction

The key objective of the research outlined in this paper is to use Wireless Sensor networks (WSN) technology to monitor a beehive colony and collect key information about the activity/environment within a beehive, and the health of the bees. As honey bees are vital pollinators for agriculture globally [1], an understanding of how to maximise their life span, ensure good hive conditions, and prevent the spread of disease/pests is potentially worth millions of Euro to the Irish and European economies, and billions of Euro worldwide. The EU parliament noted in resolution T6-0579/2008 that 79% of food is dependent on honey bees, though their population continues to decline globally. Despite this concern about honey bees, there is no scientific consensus on a single cause of the collapse in bee colony numbers.

Recently technological advances have caused embedded sensing, computing and communication devices to become an integral part of daily life. WSN has been recognised as the most emerging and interesting technology for developing the internet of things (IoT). WSN have found applications in nearly every aspect of life, including smart homes, security, and personal healthcare. This versatility has greatly increased its popularity in industrial and academic research [2], [3]. New WSN products from leading technology companies are fuelling the next wave of exponential growth in the consumer market [4], [5]. For this reason there is an increasing quantity of off-the-shelf WSN devices which can be bought as ad hoc solutions to act as specific or generic wireless sensor nodes to develop a wide range of applications.

In this paper a multi-dimensional monitoring process was developed. Heterogeneous sensors were deployed, monitoring the conditions inside the hive (temperature, CO2, pollutants etc.). Data were collected periodically, showing how the colony behaviour changed over time. This resulted in a range of engineering challenges, including multi-radio communications, low energy performance, and novel sensor combinations. The key research questions during development were: what combination of sensors will provide the most complete picture of the hive conditions, and how can the system be integrated into the hive with minimal impact on the bee colony?

The contributions described in this paper are as follows: utilising WSN technology in a novel application for monitoring beehives; a complete system solution from the sensors to the cloud; extended automatic monitoring of a beehive with a diverse range of sensors for an improved understanding of the factors that control disease development; unobtrusive sensing of a beehive with no change in the normal operation/maintenance operations; analysis of collected data from engineering and biological perspectives; and a review of system energy performance for energy neutral operation.

This paper is organised as follows: section 2 describes recent related work in the area. Section 3 presents an overview of beekeeping in the context of this research. Section 4 details the requirements identified for the WSN. Section 5 outlines the design of the developed system. Section 6 describes the test deployment. Section 7 presents some of the results gathered, evaluation of data, and concludes the paper.

II. Related Work

Honey bee venom, propolis, and beeswax are by-products used widely in health and therapy applications [6]. The lifecycle and activities of honey bees have been used as a model to inspire combinational optimisation problems in computer science and engineering [7]. The most important role of honey bees today, however, is that of a key pollinator of crops in nearly every part of the world. Pollination is valued at €155 billion to the world economy yearly [8]. The amount of pollinator-dependant crops grown worldwide has increased dramatically in the last 50 years (300%), but the number of honey bee colonies has not grown sufficiently to match this [1].

The declining population of honey bees comes as a result of reduced beekeeping, climate change, increased spread of disease and, according to some, pesticides/fungicides. Some diseases and pests have become prolific in recent years, most notably the varroa mite, the small hive beetle, *Nosema ceranae*, and colony collapse disorder (CCD). CCD has had a dramatic effect on the production of honey and pollination. The cause of this disorder has not been identified with certainty. Pesticides and other agricultural chemicals are increasingly linked to CCD [9] leading to an EU wide ban on pesticides, fungicides are now being linked to *N. ceranae*. Work by Pettis *at al.* [10] indicates that fungicides may increase susceptibility to the *N. ceranae* which has been increasingly linked to CCD. To better understand the causes of these disorders it is proposed to undertake a study where beehive conditions, as well as the conditions of the surrounding environment, are continuously monitored over a long period of time without disturbing the colony. WSN is an ideal technology for such a study as it supports low power, long term deployments.

In [11] a long term, large scale, deployment for environmental monitoring using commercially available software which was in place for one year, the network yield was found to reduce over time to <50% due to network hot spots. The platform described in this paper has a much more reliable yield, as well as using multi-radio technology to provide a remote, near real time indicator of the network performance. In [12] the issue of using the duty cycle window to achieve low power operation in a master/slave star network has been explored. A fine-tuned duty cycle window, as well as multiradio operation and energy harvesting have been employed in this work to secure the long term viability of the deployment.

III. Beehives & Beekeeping

Honey bees have played a key role in human activities since the dawn of civilisation, with important parts to play

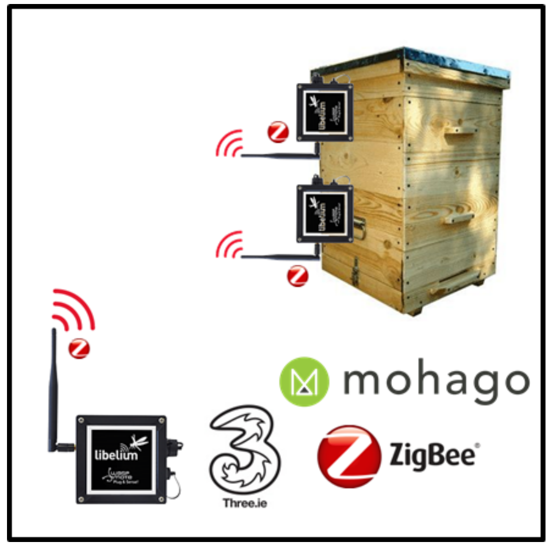

Fig. 1. Bee sensor network concept

in agriculture, medicine, nutrition, social studies, and even computer science and engineering. Keeping honey bees to produce honey has taken place in almost every culture throughout history. Ireland has a well-documented, historic tradition of beekeeping shown clearly in ”An Bechbretha”, or beejudgements [13], early (7th Century - Early Mediaeval Ireland) Irish laws relating to beekeeping. Today beekeeping remains a popular activity worldwide. The most common hive design in Irish beekeeping is the National hive which resembles the hive shown in Fig. 1.

The theoretical framework of this project related to understanding the effect of the environment/technology on the honey bees in the hive, as well as understanding how honey bees behave, through WSN technology. Taking an interdisciplinary approach, provided by collaboration between engineers and biologists, to create a complete framework for honey bee studies using a unified methodology, this research will provide honey bee data on a unique range and scale. Analysis of these data will provide insights into diseases and pests as they naturally affect the deployment hives. Insight gained can be used to develop new beekeeping methods, or identify potentially toxic chemicals entering the hive. This would help preserve, or boost, the bee population; protecting valuable pollination dependant crops and increasing yield. The work outlined in this paper describes the first step in achieving these goals, developing a prototype system for monitoring internal conditions of the hive.

IV. System Requirements

The key engineering objective of the research outlined in this paper was to use WSN technology to monitor a beehive colony. The key areas for development were identified, namely low energy performance, multi-sensor capability, multi-radio communications and in network signal processing. Fig. 1 shows the proposed WSN cloud interface with beehives, which has been designed and implemented.

To achieve this, a multi-dimensional monitoring process was envisioned. Heterogeneous sensors were deployed, moni-

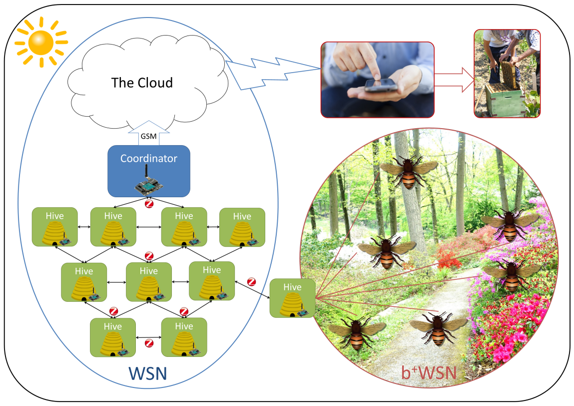

Fig. 2. B-Cool: From the Hive to the Cloud

toring the conditions inside the hive. The advantage of WSN technology is that data collection is preformed unobtrusively, without opening the hive, which would disturb the bees/change hive conditions. The work outlined in this paper describes the design and implementation of the initial sensor network which monitors the internal conditions of the hive though a diverse set of sensors. A review of the compatible sensors available for the project was performed in conjunction with the biologist to identify the optimum combination. The final combination of sensors included gas level detection and internal environment monitoring (temperature/humidity/dust particles).

The envisioned system shown in Fig. 1 had several nodes deployed within the hive, enabled with a low power radio (Zigbee) for local communication to a central base station. This base station has a long range radio (3G/GSM) in addition to the short range radio. This allows the local network to be scalable while remaining low power. Each of the nodes was expected to have a long life and eventually energy neutral operation, making a low power radio key to the design.

The deployment site network fits into a larger network where the base station from each deployment uploads data to a remote server through the 3G/GSM connection as shown in Fig. 2. The beekeeper is then able to access this server via a web page/mobile application to examine the hive conditions remotely. This information allows beekeeping decisions to be made with accuracy and speed. Another important implication of this research is to reduce the need for beekeepers to travel long distances to apiaries for inspection.

Several necessary properties were identified for the system:

- Non-invasive, minimum impact on hive and honey bee colony. This is necessary to avoid a negative effect on colony health, production and size.
- Does not disturb/prevent typical beekeeper activities. The system must not impede regular inspection of the hive, and the beekeeper must be able to have quick access to the hive in the event of an emergency.
- Robust and resistant to hive conditions. The beehive is a hostile environment for electronics/batteries as it is hot and humid. Honey bees also cover anything within the hive for extended periods in propolis and/or wax, which could impact sensor readings.

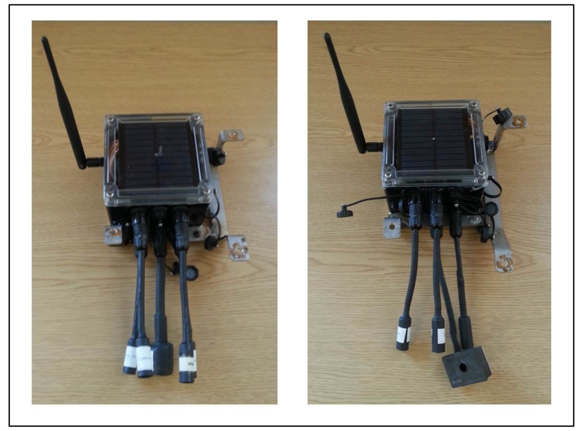

Fig. 3. Sensor nodes deployed in hive

- Low energy operation & energy harvesting. In order to satisfy this objective several methods were employed including energy harvesting techniques, extreme low power sleep cycles, low power/minimal use of power hungry sensors, and duty-cycled wireless communications.
- Suitable for remotedeployment. Beehives and apiaries are often placed in isolated locations, and the design of the system needs to reflect this property.

V. Experimental Design

To satisfy the above-described system requirements a prototype system was developed. The platform selected was the Libelium "Waspmote" v1.2 platform. This is a low power (0.7 μA) ATmega based platform, with a modular architecture allowing a combination of over 70 sensors and 11 radio technologies, a built in SD card slot, real time clock, and accelerometer. It has sleep and hibernate modes, and an energy harvester adaptor. An encapsulated version of the platform is available with a waterproof IP65 enclosure.

Two end devices were developed, a general hive conditions node and a gas detection node, both of which can be seen in Fig. 3. These nodes were designed using the Waspmote v1.2 platform with a sensor expansion board (one "Smart

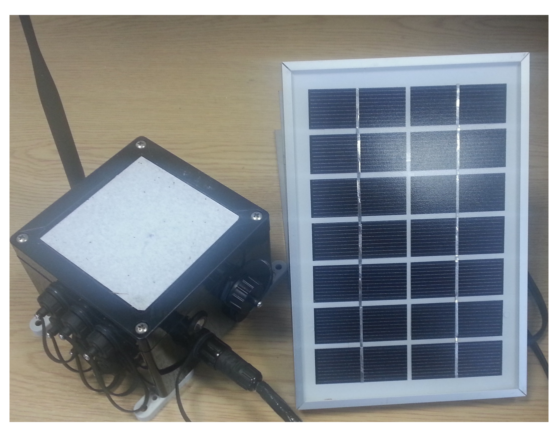

Fig. 4. Base Station, mounted outside of apiary

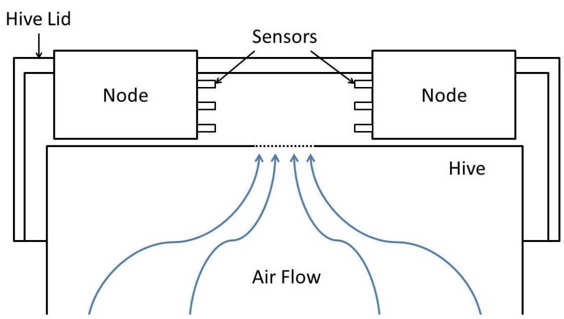

Fig. 5. Proposed layout of sensors in hive lid

Fig. 7. Photograph of final lid with sensors

Cities” board and one ”Gases Board”), a low power XBee Series 2 radio, and a waterproof capsule including a solar panel for energy harvesting (111X91mm, Max output 6.5V at 205mA) and a 6600 mAh battery. The left image is the gas detection node. It has five sensors capable of measuring the composition of the air in the hive. These sensors are: Molecular Oxygen (O_2) Sensor SK-25; Carbon Dioxide (CO_2) Sensor TGS4161; Nitrogen Dioxide (NO_2) Sensor MiCS-2710; and two Air Contaminants Sensors TGS2600 and TGS2602 which sense a range of contaminant gases the most significant of which are Ethanol (CH_3CH_2OH), Hydrogen Sulphide (H_2S), Isobutene (C_4H_{10}), Toluene ($C_6H_5CH_3$), Ammonia (NH_3), Carbon Monoxide (CO), and Methane (CH_4).

The right image in Fig. 3 shows the general hive conditions node, which utilises the Libelium ”Cities” sensor interface board, including 3 external sensors: Particle Dust Sensor (GP2Y1010AU0F), Humidity Sensor (808H5V5), and Temperature Sensor (MCP9700A). This node also utilises the Waspmote platform’s built in 3-axis accelerometer (LIS331DLH).

Both of the in-hive devices discussed above were deployed with firmware, in embedded C for the Atmel ATmega microcontroller. This firmware controls the sampling and communication schedules. An illustration of the cycles can be seen in Fig. 6. Each sensor is read at a rate of 6 samples/day, selected to minimise use of power hungry sensors while giving a clear picture of the changing parameters throughout the day. This sampling rate is the minimum sampling interval required to monitor conditions in the hive (pre-nectar/pollen honey collection in the morning, peak of nectar/pollen collection at noon/early afternoon, end of nectar/pollen collection period, night time when all the bees are in the hive), particularly given the changeable Irish climate, with the weather changing almost hourly, which could affect colony behaviour.

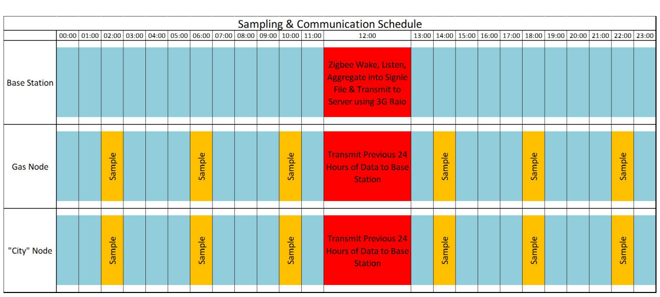

Fig. 6. Sampling & Communication Schedule for Nodes

The data were stored on the local SD card for backup, and samples from the previous 24 hours were transferred to the base station at 12:00 each day (at peak energy harvesting for solar). Each data point was time stamped as it is sampled, and as it was transferred through the network. This ensures an accurate picture of the changing beehive conditions is obtained. The total size of data transferred per day was ∼4 kilobytes. These nodes were integrated into the existing hive lid as shown in Fig. 5. The mesh shown between the lid and main hive cavity allowed the sensors to effectively observe the hive conditions without allowing the honey bees access to the sensors. The developed prototype for deployment can be seen in Fig. 7.

The final node developed was the base station (Fig. 4), also developed using the Waspmote v1.2. This unit featured the Waspmote platform, a low power XBee Series 2 radio as well as a GSM/GPRS/3G module model SIM5218E (SIMCom). This node acts as the ”bridge” between the Zigbee and 3G networks. The firmware is duty cycled to wake and receive data from the hive nodes, combine them into a .csv file and upload via FTP to a server located in the Engineering building at University College Cork. The base station featured a solar panel (234X160mm, Max output 7V at 500mA) to support the second radio module and a 6600 mAh battery.

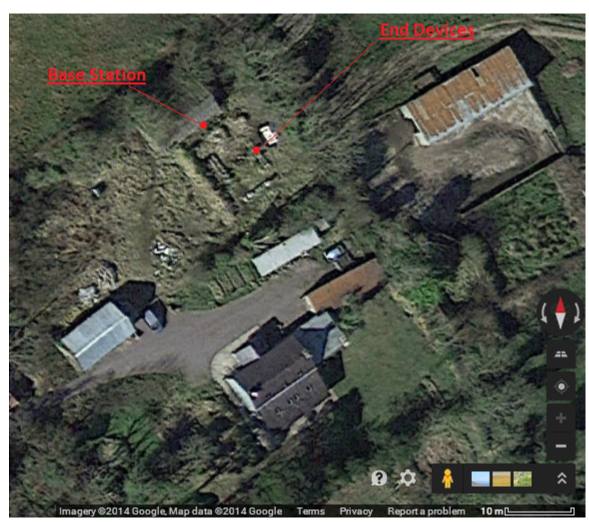

Fig. 8. Deployment site map, Imagery & Map Data courtesy of Google

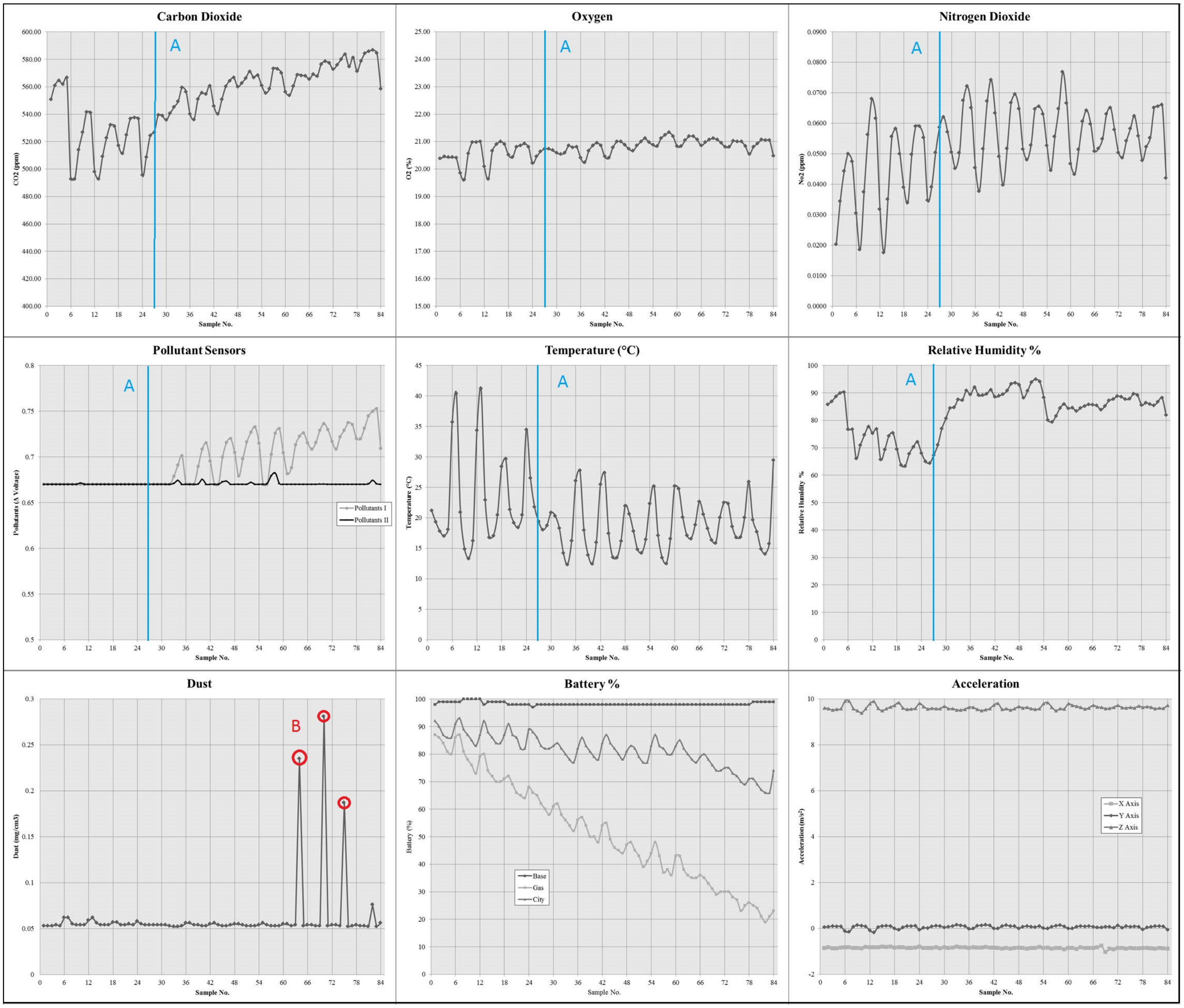

Fig. 9. Data collected over 14 day deployment, every 6 Samples (vertical grid lines) corresponds to 24 hours

VI. Deployment Results, & Analysis

The first deployment took place in Lyre, Co. Cork, Ireland (Fig. 8) from 29/06/2014. The first two weeks of data are presented in Fig. 9, and were used to evaluate the performance of the system and inform decisions for future deployments. This is the site of an established apiary with a suitable hive for monitoring. The 3G service provider selected was Three Ireland, selected for its strong 3G coverage in rural Ireland as a result of the National Broadband Scheme (NBS). Throughout the deployment there were several days of varying weather, which allowed the system's performance under different conditions to be evaluated. The first 5-6 days were warm and dry. After this point rainfall increased while temperatures stayed high. The change in weather is marked on relevant graphs with a line labelled "A".

The undesired gas sensors (Nitrogen Dioxide (NO_2), Carbon Dioxide (CO_2) and pollutants) show a clear diurnal pattern. This is believed to be a result of the typical daily variation in the number of honey bees in a hive as they forage and the fact that all the bees remain in the hive at night. The gas sensors shown in Fig. 9 show the expected result that the oxygen levels in the hive (O_2) remained constant despite the changing conditions. Honey bees are known to dedicate a lot of energy to keeping their hive well ventilated; they vary their hive's air gaps by adding or removing wax, and use their wings in a "fanning" motion to force air flow throughout the hive.

The data on temperature show the high temperatures which the inside of the hive can reach on a warm day, particularly if there is little wind. Overheating is a major concern for beehives as it can reduce the condition of the brood (bee larvae), as well as impacting the quality and stability of the hive's wax combs. Thermal regulation is the second reason for the ventilation behaviour of the colony described above. Humidity is also a key parameter for the health of adult honey bees and the

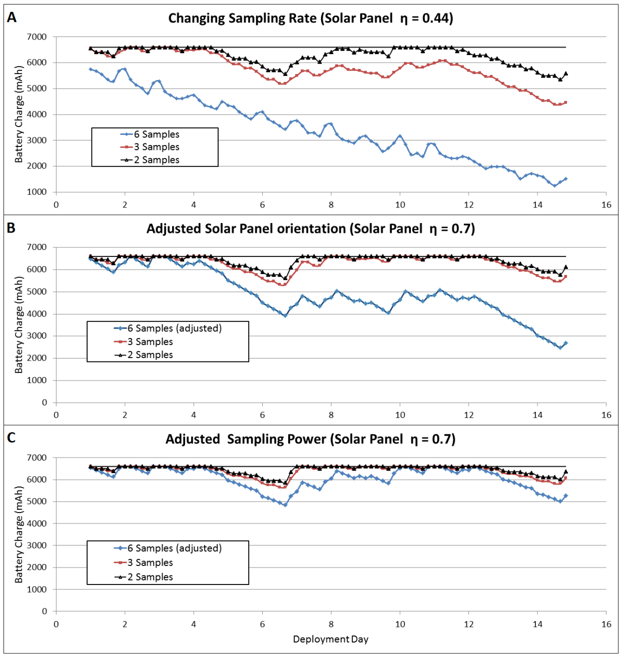

Fig. 10. Improving energy performance of the gas node

brood. From the collected data it was observed that the weather changes have a strong influence on the in hive humidity. Inspections of the hive during the deployment found that the honey bees were plugging some of the vents with a pollen and propolis mixture. The dust sensor used is sensitive to pollen particles and it detected relatively constant levels initially, but founds spikes in dust density (graph labelled "B") towards the end of the deployment which may be reflecting this behaviour. Further deployments will be required to validate this. The accelerometer did not detect any movement of the hive (e.g. from the hive being stolen or knocked over by a gust/animal) which was to be expected as it was well secured on a stable platform. It is expected in future to use the accelerometer to detect such movements, as well as high frequency sampling to observe hive vibrations from bee activity within the hive.

The performance of the solar energy harvesting was observed by monitoring the battery level throughout the deployment. It is clear that the energy harvester did not provide enough power for the gas sensing node, due to the power hungry gas sensors which need to be powered for an extended time before they can provide an accurate result. In Fig. 10 the options for improving this energy performance were explored, including reducing the rate of sampling (labelled A), maximising solar panel efficiency by deploying it at an angle optimised for the deployment location (labelled B) (38° from vertical for Ireland, latitude $\sim$50°), and improving the power consumption of sampling by 30% through reducing idling time and changing the order of sensor readings (labelled C). It was found that utilising these techniques energy neutral operation could be achieved for the end devices.

VII. Conclusions & Future Work

In this paper a complete WSN solution for monitoring parameters within a beehive has been described, along with some results collected from an initial deployment. These results have been analysed and the typical activity within the colony has been identified in the collected data. Some improvements for energy performance of end devices in future deployments have been proposed. The base station (Zigbee and 3G radio) has achieved fully energy neutral operation through utilisation of a larger solar panel, and a duty cycle as low as 4%. Future work will focus on expanding the sensor range of the network, including developing some dedicated sensors for beehive monitoring. The proposed energy improvements form part of the ongoing redesign of the smart hive. Expanding the energy harvesting options of the network from solar harvesters alone will also be key to ensuring the longevity of deployments. A second deployment at the University College Cork, Ireland campus is planned to begin in 2015.

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