Successful Deployment of a Wireless Sensor Network for Precision Agriculture in Malawi

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***Abstract*—This paper demonstrates how an Irrigation Management System (IMS) can practically be implemented by successfully deploying a Wireless Sensor Network (WSN). Specifically, the paper describes an IMS which was set up in Manja Township, City of Blantyre based on an advanced irrigation scheduling technique. Since the system had to be self-sustained in terms of power, which is a challenge for deployment in rural areas of developing countries like Malawi where grid power supply is scarce, we used solar Photovoltaic (PV) and rechargeable batteries to power all electrical devices in this system. The system incorporated a remote monitoring mechanism through a General Packet Radio Service (GPRS) modem to report soil temperature, soil moisture, WSN link performance and PV power levels. Irrigation valves were activated to water the field. Our preliminary results have revealed engineering weakness of deploying such a system. Nevertheless, the paper shows that it is possible to develop a robust, fully-automated, solar powered, and low cost IMS to suit the socio-economic conditions of small scale farmers in developing countries.**

***Index Terms*—WSN deployment, precision agriculture, soil moisture, solar power, water scarcity**

I. INTRODUCTION

IN Precision Agriculture (PA), various parameters including soil type and temperature vary dramatically from one region to the other and therefore any irrigation system must be flexible enough to adapt to the constraints. Unlike off-the-shelf irrigation controllers which are usually expensive [1], [2] and not effective in managing scarce water resources, an Irrigation Management System (IMS) based on Wireless Sensor Network (WSN) can accept any desired irrigation scheduling strategy to meet specific environmental requirements. However, WSNs are still under developmental stage; as such, they are at times unreliable, fragile, power hungry and can easily lose communication [2] when deployed in a harsh environment like agricultural field. Unlike laboratory based simulations and experimental installations, practical deployment has to handle such challenges to be fully beneficial. WSNs have an immense potential to PA; such that, if well designed, can be a solution to a low-cost IMS suitable for developing countries.

The rapid increase in WSN deployment in industrial, agricultural and environmental monitoring applications is as a result of being a low power and low data rate hence energy efficient technology. It also offers mobility and flexibility in connectivity which promote network expansion when needed.

Recently, there have been numerous publications on the application of WSNs to PA. Keshtgary and Deljoo [3] discussed the simulation of WSN for agriculture using OPNET simulation tools in which random and grid topologies were compared. They evaluated the performance of the networks by monitoring delay, throughput and load. This approach, however, lacks practical aspects where flaws become absolutely inevitable. Zhou and others [4] presented a WSN deployment for irrigation system using ZigBee protocol. This study did not consider monitoring the performance of communication links between sensor nodes which is vital in practical deployments as it impacts battery life. Despite having a detailed design for the powering side, it is not clear whether they monitored battery levels for the sensor nodes or not.

Our paper revisits the problem of the field readiness of WSNs when deployed in PA to assist small scale farmers of the rural areas of developing countries. The main contribution of this paper is the design, implementation, and performance of a low-cost but efficient IMS that combines sensors and actuators in a wireless sensor/actuator network so as to guide successful deployment of WSNs for PA.

The remainder of the paper is organized as follows: section II presents the design of the Wireless sensor network for Precision Agriculture in Malawi (WiPAM); section III presents the performance evaluation of the underlying WSN development; section IV discusses challenges and experiences we acquired from the WSN practical deployment; and finally, conclusion and future work are presented in section V.

II. THE WIPAM DESIGN

The ultimate purpose of the WiPAM system was to automate irrigation process. Specifically, we were interested in studying fluctuations in soil moisture and temperature in the agricultural field. Consequently, sensor data were automatically gathered at intervals of 2 minutes or 30 minutes depending on whether the irrigation was in progress or not. The data were retrievable at the end of the observation period. Based on the results, the irrigation system switched on a valve and finally irrigated the field. The rest of this section describes the system architecture used to meet these requirements and the different components of the system.

The general work-flow of the system consists of (1) taking soil moisture and temperature samples at predefined time intervals, (2) sending and storing sampled data in a coordinator

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node, (3) sending the data from the coordinator to a gateway node for forwarding to a remote server through a cellular network, (4) going to sleep, and (5) waking up and repeating the previous steps. Depending on the values stored in the coordinator node, the irrigation valves have to be opened or closed.

This work-flow can be mapped into a five-layer system architecture depicted by Fig. 1 which includes soil moisture sensor, wireless sensor node, coordinator node, irrigation system, and gateway node. In subsection (A) we first discuss the WSN protocol and topology used, after which we describe the single components of the WiPAM in subsections (B) through (F).

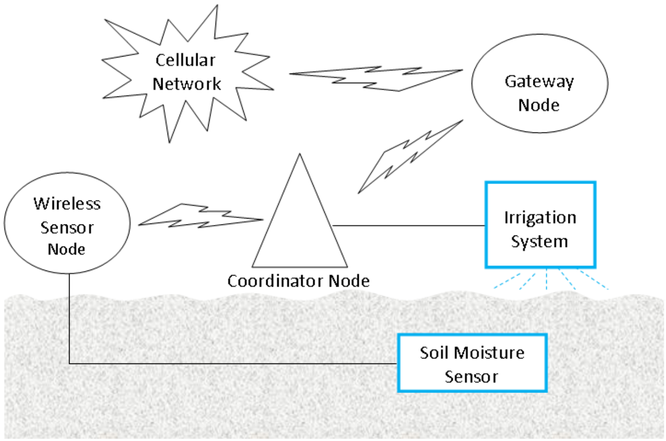

Fig. 1: System architecture

A. *WSN protocol and topology*

The WSN deployed in this study used ZigBee, an IEEE 802.15.4 networking standard for Personal Area Networks. The physical (PHY) layer of ZigBee operates in the unlicensed Industrial, Scientific and Medical (ISM) radio bands of 868 MHz, 915 MHz and 2.4 GHz depending on the region. The ISM band in Malawi is 2.4 GHz; hence this research adopted this band.

The main focus of ZigBee protocol is on low cost and low power consumption. The low power consumption characteristic is really appealing since sensors are usually placed at a remote location where battery power supply is the only option and needs to be sustained. To achieve low power consumption the ZigBee protocol operates at low data rates (250 kbps at 2.4 GHz). Nonetheless, this could be its limitation if high data transmission applications are inevitable. Such applications may use other IEEE standards for instance Bluetooth (802.15.1) and WI-FI (802.11) which offer high data rates of 1 Mbps and 54 Mbps respectively, but at the expense of battery power. Nevertheless, in PA, sensor data do not require wide bandwidth since it is needless to continuously monitor soil moisture and temperature as there could be no significant changes in these parameters in a short period. Hence, ZigBee is well suited for PA in remote areas where battery life as long as a couple of months may be required.

Depending on the situation and environment, ZigBee networks can take three forms of topologies: Star; Cluster-Tree; and Mesh. A star topology comprises one ZigBee Coordinator (ZC) and several other ZigBee End Devices (ZEDs). No ZigBee Router (ZR) is required in this topology. The ZC communicates with all ZEDs, and there is no direct messaging between ZEDs (refer to Fig. 2). On the other hand, a cluster-tree topology is made up of one ZC and several child nodes which are ZRs and ZEDs [5]. Apart from communicating with its parent node, the ZR may as well have its own child nodes, but there is only one path between any pair of devices in this network. A mesh network is achieved by allowing devices in the cluster-tree topology to communicate with each other using multiple routes. In this way devices are able to send and receive messages reliably even when their preferred path is down or congested. This is the major advantage of a ZigBee mesh network over star and cluster-tree networks. However, a mesh network has no guarantee of bandwidth since no synchronisation is used which requires disabling of beacon mode.

Since the network for this study was small, having five devices placed within short distances (7 m), we chose a star topology (refer to Fig. 2) in which all the four in-field sensor nodes were ZEDs and one node was configured to be a ZC, and it was used to aggregate data and actuate irrigation valves accordingly. With this topology, there is a considerable potential of battery life saving since all ZEDs spend most of their time asleep, only waking up to make measurements and send the data to the ZC. Otherwise, as the case with cluster-tree and mesh, ZRs need to be awake since they provide paths for other devices to the ZC thereby wasting battery power in the process.

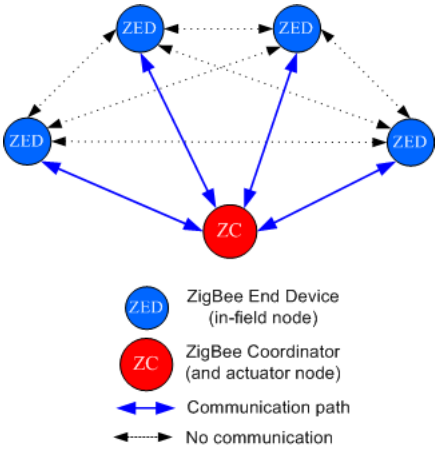

Fig. 2: Star network topology

B. *The Soil Moisture Sensor*

The soil moisture sensor is one of the most important components upon which the efficiency of the irrigation activity heavily relies. The suitability for a soil moisture sensing device depends on the cost, reliability, ease of interfacing to a signal processing device, accuracy and soil texture. Although it is not possible to single out a sensor that satisfies all of the above selection criteria, we opted for the Watermark 200SS (Irrometer Company, Inc., Riverside, CA) which scores highly on low cost (EUR 45), durability, maintenance-free operation and suitability for soil texture variability since it has a wide measuring range (0 to -239 kPa) [6]. The fact that this sensor monitors water potential makes it superior to other water-content based sensors; knowledge on soil water content is not as important as knowing the level of tension crop roots must exert to extract such water.

The measurement of the Soil Moisture Potential (SMP) using Watermark 200SS sensor is done through two stages: (1) reading the frequency of the ac signal pushed into the sensor which is then converted to resistance; and (2) using a non-linear calibration equation to convert the Watermark electrical resistance (in kΩ) into SMP (in kPa).

Sensor positioning in the root zone of the plant is absolutely crucial, and it determines the amount of water to be applied during each irrigation event. A sensor placed well deep into the soil allows the irrigation system to apply more water up to that depth beyond plant roots; the water below plant roots is lost through deep percolation. On the other hand, a quite shallow sensor promotes light irrigation with a consequence of the system failing to apply water into the root zone, and plants will therefore be stressed. In view of the fact that maize is a deep rooted crop with approximate maximum rooting depth ranging from 75 cm to 120 cm [7] depending on the characteristics of the soils like presence of restrictive soil layers, we considered placing the soil moisture sensors at a depth of 40 cm where, according to [8], about 70% of water uptake by crops takes place.

C. The Wireless Sensor Node

As a wireless sensor node we decided to opt for an Open Wireless Sensor Network (OWSN) node for the advantages that OWSNs have to offer. The advantages of the Open Source model when applied to WSNs is relevant in terms of cost, personalisation and independence from a single entity as compared to proprietary solutions. In particular, we chose the Waspmote node by Libelium. Waspmotes are built around XBee transceivers which provide flexibility in terms of multiplicity of operating power, protocols, and operating frequencies. According to [9], other Waspmote characteristics include (1) minimum power consumption of the order of 0.7 µA in the hibernate mode; (2) flexible architecture allowing extra sensors to be easily installed in a modular way; (3) the provision of Global Positioning System (GPS), General Packet Radio Service (GPRS) and Secure Digital (SD) card on board; and (4) the provision of a Real Time Clock (RTC). Furthermore, Waspmotes are powered with a lithium battery which can be recharged through a specially dedicated socket for the solar panel; this option is quite interesting for deployments in developing countries where power supply is either scarce or unstable.

We deployed four sensor nodes; two in each of the two plots of 8 m x 7 m in size (refer to Fig. 3). Since the moisture sensors were coupled to the wireless sensor nodes, it was of great importance to instal the nodes at appropriate locations to take into account the variability of spatial distribution of water in the field. To satisfy this requirement we positioned sensor nodes as shown in Fig. 3. While it is shrewd to consider placing sensor nodes in the mostly dry locations of the field to avoid stressing crops in those locations, but caution should also be exercised to avoid over-irrigation of the other parts of the field. Consequently, based on topography, it may be necessary to divide a large field into smaller zones which can effectively be controlled and irrigated independently.

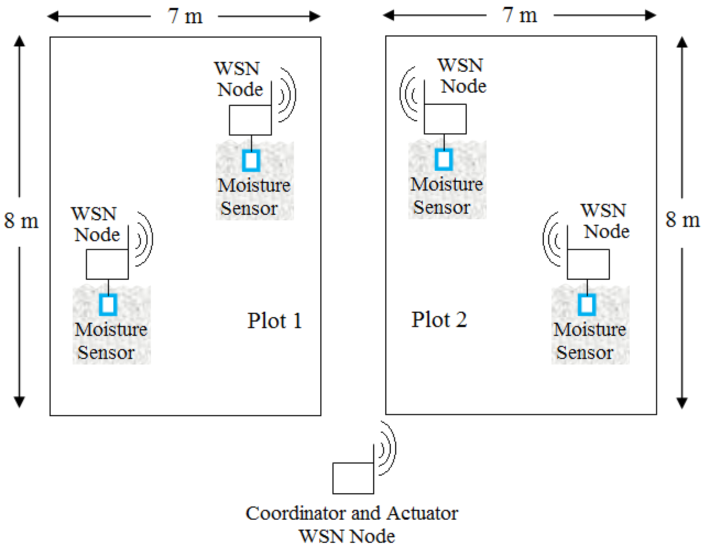

Fig. 3: Sensor location in the field.

A software program was developed and uploaded into the sensor nodes to allow them to measure soil moisture, their battery level, and soil temperature at time intervals of 30 minutes when the system was idle and 2 minutes when irrigation was taking place. The rest of the time sensor nodes were in deep sleep mode to conserve battery power. Once the measurements were done, the nodes relayed the data through the XBee transceivers to the coordinator node for amassing and processing.

A 30 minute sampling interval was considered as a long enough time in order to preserve battery power for the nodes, but also regarded as a short enough time in order to fully monitor the soil moisture trends. In other words, increasing sampling interval saves a substantial amount of battery power for the sensor nodes but at the conceivable expense of information. However, in order to avoid over-irrigation as a result of late termination of the irrigation event due to the slow flow of water in the soil, it was judicious to reduce the sampling interval from 30 minutes to 2 minutes when the irrigation was in session so that prompt termination can be effected.

D. The Coordinator Node

We used a Waspmote equipped with a ZigBee module as a coordinator node. This component was the heart of the whole system and had several crucial roles to perform. Firstly, as the most capable node in the network, a ZC permits and sanctions all ZEDs that are in quest of connecting to its network. That is, it is responsible for network formation by assigning addresses to all joining nodes and ensuring security for the network.

As such, there must be only one ZC per any given ZigBee network.

Secondly, the ZC was used to receive and aggregate data from the four sensor nodes discussed in (C) above. The received sensor data included the Watermark frequency and the soil temperature which were used to derive SMP. The coordinator then had to make a decision on whether to irrigate or not depending on the level of the SMP. Four of the Input/Output (I/O) pins of the Waspmote's microcontroller were connected to a latching circuit and were used to initiate or halt the irrigation by sending corresponding pulses to the pins.

Finally, we used the ZC to relay the data to a gateway node for forwarding to a remote server. When receiving data from the sensor nodes the coordinator also captured the Received Signal Strength Indicator (RSSI) of every packet received. This is a measure of the quality of the link between itself and a particular sensor node. The SMP, battery level, soil temperature and RSSI from all sensor nodes together with its own battery level and system running time were aggregated and prepared suitable for Short Message Service (SMS) transmission system. Thereafter, the SMS data were relayed to the gateway for forwarding to a remote server every 15 minutes when irrigation was in progress or every 30 minutes when the irrigation system was in an idle mode.

E. The Irrigation System

The irrigation system had three components: latching circuit; solenoid valves and associated pipes; and powering system. We were compelled to use a latching circuit as a means of saving power for the coordinator node. Unlike sending and holding a pulse for the entire irrigation period which could waste battery power, the latching circuit allowed us to use a short pulse from I/O pins of the coordinator's microcontroller. The latching circuit comprised opto-couplers, switching transistors, digital NAND gates (forming RS flip-flop) and power transistors. The power transistors were used to switch ON/OFF solenoid valves where irrigation pipes were connected. We incorporated switches in the latching circuit to allow manual closing and opening of the valves in case of emergency.

We were motivated to use L182D01-ZB10A (SIRAI$^{®}$) solenoid valves because of the low cost (EUR 58.79), low power consumption (5.5 W when latched); and the possibility of using a 12 V DC power supply. The two latter features allowed us to use a single 14 W, 12 V solar panel to power both the solenoid valves and the latching circuit. This was more appealing for deployments in rural areas of developing countries where grid power supply is either scarce or unstable.

With the above arrangements, the coordinator node was able to control the irrigation by sending short pulses to its I/O pins. Specifically, two pins were dedicated for each of the two solenoid valves; in which case when initiating irrigation the coordinator had to send a HIGH pulse lasting 1 second to the latching circuit through one pin. The latching circuit had to hold this state until the coordinator sent another HIGH pulse to the other pin indicating completion of irrigation and, hence, valves should close.

F. The Gateway Node

One of the four in-field sensor nodes discussed in (C) assumed the role of a gateway used to send data to a remote monitoring site through a cellular network. In addition to a ZigBee module, we equipped this particular node with a GPRS module. Just like any other wireless sensor node in this experiment, it was capturing Watermark frequency, soil temperature and its battery level. The sensed data were sent to a coordinator for processing and aggregating with the other sensors' data. Afterwards, the coordinator sent the aggregated data back to the gateway every 15 minutes when irrigation was in progress or every 30 minutes when the irrigation system was in an idle mode. The GPRS module residing on top of the gateway node was then used to communicate with the cellular network to forward the SMS data to a remote monitoring station. Despite gathering sensor data at intervals of 2 minutes or 30 minutes depending on whether the irrigation was in progress or not, we opted for sending the data to the remote monitoring station at intervals of 15 minutes when irrigating and 30 minutes otherwise. This arrangement reduced the cost of the remote monitoring system by decreasing the number of SMSs sent considerably.

We could have used the coordinator node to send data directly to a remote server by equipping it with a GPRS module, but we were motivated to use this structure because of the following confounding issues: Firstly, the coordinator was configured to be a non-sleeping device because it was responsible for network set-up and maintenance. It was also responsible for actuating solenoid valves in addition to receiving sensor data from all other nodes in the network. As such, it was the busiest node in the network and, consequently, its battery was being depleted extensively. It was therefore necessary to offload SMS sending duties to a gateway node which, otherwise, was less loaded. Note that sending the same amount of data through ZigBee module consumes less power (2 mW) than sending through GPRS to the cellular network (2000 mW) [9].

Secondly, since the coordinator node was the heart of the whole system, its failure was very critical and constituted a single-point-of-failure phenomenon. On a regular basis, the gateway was checking the status of the coordinator and reporting any hitches directly to the personal mobile number of the management personnel. This allowed the personnel to quickly fix the problem.

III. PERFORMANCE EVALUATION

In this study we evaluated the performance of the WSN deployment as a way of assessing its field readiness in agricultural application. Firstly, we investigated the ZigBee radio link performance through measurements of RSSI at different distances of the WSN nodes and different heights of the maize plants. Secondly, we monitored battery life for sensor nodes both at night and during the day. Finally, we were interested in ascertaining whether battery life had a bearing on radio link performance or not.

A. Received Signal Strength Indicator

We assessed the performance of the WiPAM in terms of RSSI at different distances and heights of the maize plants. Zennaro and others [10] reported that RSSI is one of the three commonly used WSN link quality estimators which is a signal-based indicator, and is computed over the signal present in the channel at a particular time. The other indicators are the Link Quality Indicator (LQI) and the Packet Reception Rate (PRR). In this experiment we analysed the performance of the network based on RSSI and we used XBee-ZB modules at 2.4 GHz as radio transceivers whose sensitivity was -96 dBm [9]. This means that when RSSI goes below -96 dBm then the communication link is bound to fail.

1) RSSI over Distance: The four in-field sensor nodes were fixed but the coordinator was moved from one place to the other. In the first experiment, the coordinator node was placed in such a way that the relative distances between the respective sensor nodes and the coordinator were 23 m with all nodes placed at a height of 60 cm above the ground. In the second experiment, the coordinator was moved closer to the in-field nodes with a distance of 7 m to each node and at the same height as in the first scenario (Fig.3 shows sensor positions for this case).

Fig. 4 shows the results of the network performance in terms of RSSI expressed in dBm when the distance between sensor nodes and the coordinator was 23 m while Fig. 5 shows the same parameters when the distance was reduced to 7 m. The results show that the communication links were bound to fail when the distance was 23 m since the RSSI was at around -90 dBm which is very close to the receiver sensitivity of -96 dBm. On the other hand, it was essentially improbable for the network to fail when the distance between the nodes and the coordinator was 7 m since the RSSI was at around -58 dBm.

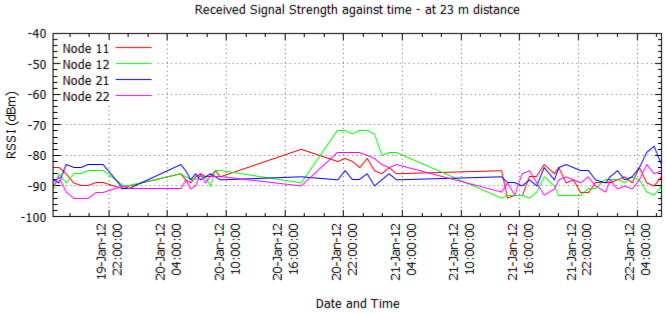

Fig. 4: Received Signal Strength against time - at 23 m distance.

Therefore, it is absolutely imperative in any practical deployment to consider placing sensor nodes in such a way that the distances between the nodes are optimized in accordance with the size of the field.

Furthermore, we noted that multipath fading which was exacerbated by the movement of wet leaves of the maize plants played a very crucial role on RSSI. This is portrayed by the wavy behaviour of the RSSI graphs shown in both Fig. 4 and 5.

2) RSSI over Height of Crops: As described in the previous section, the sensor nodes were placed at a height of 60 cm above the ground. We started monitoring the link performance when the maize plants were 50 cm tall. At the end of the experiment the crops had grown to about 200 cm thereby covering the in-field sensor nodes completely. Fig. 6 shows a scenario in which the sensor is being fully covered by the maize plants thereby posing a very serious threat on the communication link performance.

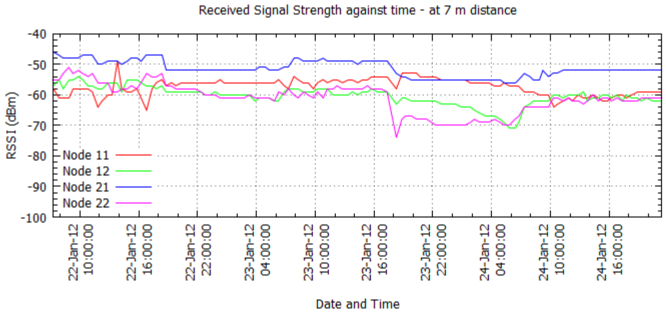

Fig. 5: Received Signal Strength against time - at 7 m distance.

Fig. 7 shows the variation of nodes' average RSSIs with crop height. The graph shows a slight decrement in the level of RSSI with time. However, as depicted by the best-fit line of the average RSSIs, there is no major degradation in the quality of the communication link corresponding to the height of the crops.

Fig. 6: Sensor node being covered by maize plants.

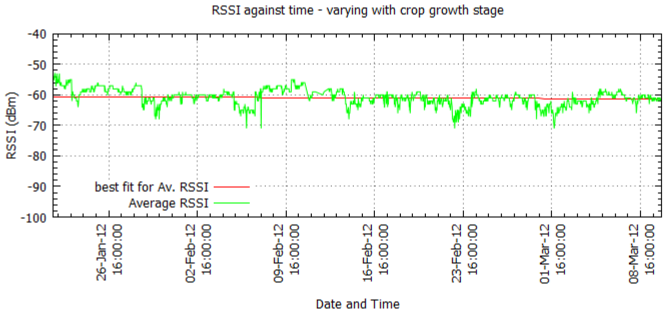

Fig. 7: Variation of RSSI with crop height.

B. Battery Level

As the system had to be self-sustained in terms of power, we used solar panels and rechargeable Li-Ion batteries to power all electronic devices in this system. After evaluating the performance of the system in terms of energy usage, we discovered that the three in-field sensor nodes which were using deep sleeping mode as a way of conserving energy were more efficient that the coordinator which was never put into sleeping mode. In spite of employing sleeping mode, the gateway node had its battery level depleted so quickly since most of its energy was being used for sending SMSs to a remote monitoring site.

We, therefore, through these experiments found that the 2.5 W solar panels were enough for the three in-field sensor nodes while the gateway and coordinator had to be powered by 5 W and 7.5 W solar panels respectively. We also changed batteries of the gateway and the coordinator from 1150 mAh to 2300 mAh and 2450 mAh respectively while 1150 mAh batteries sufficed all the other three in-field sensor nodes.

Fig. 8 shows the battery levels for all the five sensor nodes used in this experiment. Clearly, the gateway and coordinator batteries were a major concern in this deployment before the changes were effected. The graphs in this figure show that on a number of occasions (e.g. on 3rd, 10th, 12th and 18th January, 2012) the coordinator battery was depleted completely and the system had to be resuscitated by a higher capacity battery which was used for powering the valves. As depicted by the graphs, all the batteries were heavily depleted between 18th January and 22nd January when there was no sun shine due to heavy rains. It was after this point in time that the changes in the powering requirements for the gateway and the coordinator were inevitable.

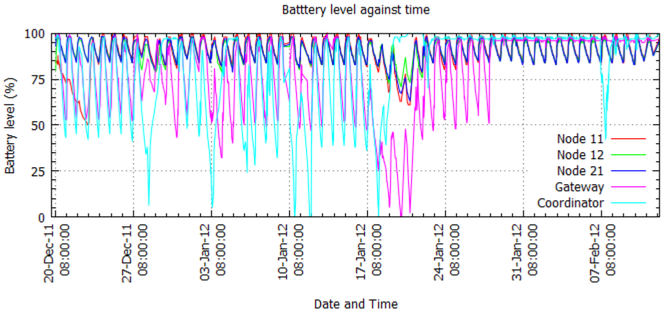

Fig. 8: Battery Levels against time.

C. RSSI Vs Battery Level

It was important to investigate the correlation between the RSSI and battery level as performance metrics. Fig. 9 shows graphs of the two in-field nodes' battery levels and RSSIs plotted on the same scale. The results show that there is a very high correlation between the battery level and the RSSI. Both battery level and RSSI peak at around 3:00 PM, and slump dramatically at around 4:00 AM. They start to peak again at around 7:00 AM when the sun rises and starts to charge batteries.

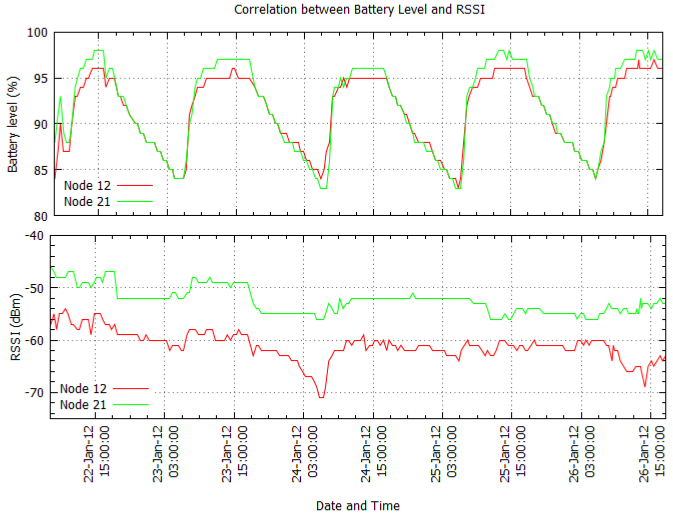

Fig. 9: Correlation between Battery Level and RSSI.

These results show a very interesting feature especially when considering the powering requirements and the required level of RSSI to achieve a specified Quality of Service (QoS) particularly in a critical application of WSNs. In other words, there should be a balance between the required level of RSSI and the expected lifetime of batteries used in any WSN deployment.

IV. CHALLENGES AND EXPERIENCES GAINED

Through this study we have gained a couple of valuable experiences which we believe can speed up the process of designing new WSN deployments for PA. Firstly, the study revealed a formidable practical challenge concerning the conflict between ZigBee and GPRS modules. When both modules were powered up, the ZigBee module was losing connection resulting in a total network failure which required manual reset. On other occasions, it was the GPRS module which was failing to connect to the cellular network. Nonetheless, using software at a gateway layer, we were able to turn OFF one module when the other was active. This was not possible at the coordinator node layer since its ZigBee module was always required to be ON to avoid losing connection with the other network nodes. Hence, we deemed it appropriate to use one of the four in-field nodes as a gateway for sending SMSs rather than the coordinator node.

Secondly, there was a daunting challenge of powering requirements for the sensor nodes which, on several occasions, required site visit to resolve the problem. The batteries were being heavily depleted especially for the coordinator and gateway nodes. The system, nonetheless, became remarkably resilient to power failure after we had increased the battery capacity for the gateway and coordinator nodes. We further increased the robustness of the system by increasing the sampling time from 5 minutes to 30 minutes when in idle mode and from 1 minute to 2 minutes when irrigating. This implies that where power supply is limited, or in order to reduce the cost of WSN deployment through the use of low capacity batteries and small sized solar Photovoltaic (PV) panels, one needs to consider increasing sampling time. Based on this feature, we conclude that for a large network it will be shrewd to divide the system into several independent sub-networks so that no single node is used to amass the data from all the other nodes. We also noted that keeping distances between sensors as short as possible can improve battery life tremendously.

Finally, a very crucial requirement of any WSN deployment is close monitoring. Rather than conducting physical site visit, which is not only time consuming but also expensive, we were motivated to monitor the system performance remotely. This was imperative as we could identify system faults in real time and swiftly conduct pre-emptive maintenance by visiting the field only when needed. We believe that any successful WSN deployment must involve remote monitoring through a cellular network which is broadly available even in rural areas of developing countries.

V. CONCLUSION AND FUTURE WORK

In this paper, we have demonstrated how an IMS was implemented based on WSN. We further evaluated the performance of the design in order to develop a more robust and sustainable system considering the challenges that any practical deployment would pose. Specifically, we explored the lifetime of the batteries, RSSI and the correlation between the two. We discovered that sensor battery lifetime has serious repercussions on the robustness of WSN deployment since it directly erodes RSSI. We have also shown that sensor placement in the agricultural field has to be in such a way that the distance between the nodes is a minimum whenever it is possible in order to improve the resilience of the system remarkably.

As future work, we propose large scale deployment to observe the impact on the role of the ZC node in handling numerous queries from the in-field sensors. Since WSNs are flexible on the software layer and, hence, can accept any scheduling strategy, we further propose that future deployments should focus on the water application efficiency in order to reduce the energy used in irrigation water pumping. It is envisaged that this will foster installations of low-capacity solar PV water pumping systems for irrigation to suit the socio-economic conditions of small scale farmers in developing countries.

Furthermore, while it would be interesting to explore the practical performance of WSN irrigation systems in other areas of Malawi, we believe that such set-ups would compare well with the current deployment in Blantyre because Malawi, as a small country, experiences almost evenly distributed weather conditions.

ACKNOWLEDGMENT

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