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

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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 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 via a 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 the developing world.**

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

## I. INTRODUCTION

IN precision agriculture, 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 the constraints. Unlike off-the-shelf irrigation controllers which are usually expensive [1], [2] and not effective in managing scarce water resources, an irrigation system based on WSNs can accept any desired irrigation scheduling strategy to meet specific environmental requirements. However, WSNs are still under development 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 fields. Unlike laboratory based simulations and experimental installations, practical deployment has to handle such challenges to become full beneficial. WSNs have an immense potential to precision agriculture; such that, if well designed, they can be a solution to a low-cost IMS suitable for the developing world.

Recently, there have been publications on the application of WSN to precision agriculture. 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 unexpected traps are inevitable. Zhou and others [4] presented a WSN deployment for irrigation system using ZigBee technology. This study did not consider monitoring the performance of the communication links between sensor nodes which is very 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.

This paper revisits the problem of the field readiness of WSN when deployed in precision agriculture to assist small scale farmers of the rural areas of the developing countries. The main contribution of this paper is to present the design, implementation, and performance evaluation 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 precision agriculture.

The remainder of the paper is organized as follows: section 2 presents the design of the WiPAM while section 3 discusses how the WiPAM was implemented; section 4 presents the performance evaluation of the underlying wireless sensor network development; and finally, conclusion and future work are presented in section 5.

## II. THE WIPAM DESIGN

The ultimate purpose of the WiPAM system is to automate the irrigation process. Specifically, we were interested in studying fluctuations in soil moisture and temperature. Consequently, sensor data was automatically gathered at intervals of 30 minutes 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 workflow 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 node, (3) sending data from the coordinator node to a gateway that forwards it to a remote server via cellular network, (4) going to sleep afterwards and (5) waking up and repeating the previous steps. Depending on the values stored in the coordinator node (2), the irrigation valves have to be opened or closed.

This workflow can be mapped into a five-layer system architecture depicted by Fig. 1 which includes (A) soil moisture sensor, (B) wireless sensor node, (C) coordinator node, (D) irrigation system, and (E) gateway node. Following is a description of the single components.

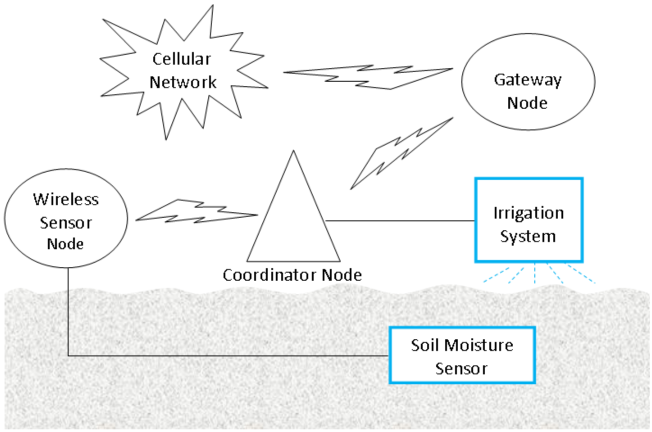

Fig. 1. System architecture

### A. The Soil Moisture Sensor

The soil moisture sensor is one of the most important components upon which the efficiency of the irrigation activity depends. The suitability for a soil moisture sensing device depends on the cost, reliability, ease of interfacing to the mote, accuracy and soil texture. Although it is not possible to single out a sensor that satisfies all of the selection criteria, we opted for the Watermark 200SS (Irrometer Co.) 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 -200 kPa). 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 resistance measurement from this sensor, however, can only be read by an AC signal. The measurement of the water potential 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 k$\Omega$) into Soil Moisture Potential (SMP) (in kPa).

Sensor positioning in the root zone of the plant is very crucial as it determines the amount of water to be applied. 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, shallow sensors promote shall irrigation and fail to apply water into the root zone, and plants will be stressed. In view of the fact that maize is a deep rooted crop with approximate maximum rooting depth of 75 to 120 cm [5] depending on the characteristics of the soils (e.g. presence of restrictive soil layers), we considered placing the soil moisture sensors at a depth of 40 cm where, according to [6], about 70% of water uptake by crops takes place.

### B. The Wireless Sensor Node

As wireless sensor node we decided to opt for an Open Wireless Sensor for the advantages that OWSN have to offer. 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. Other Waspmote characteristics include (1) minimum power consumption of the order of 0.7 $\mu$A in the Hibernate mode (2) flexible architecture allowing extra sensors to be easily installed in a modular way (3) the provision of GPS, GPRS and 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 not stable.

We deployed four sensor nodes; two in each of the two plots of 8m x 7m in size (refer to fig. 2). Since the moisture sensors were coupled to the wireless sensor nodes, it was of importance to consider the location of the sensor nodes in the field. Fig. 2 shows the locations of the sensors in the field to take into account the variability of spatial distribution of water. 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 be exercised to avoid over irrigation of the other parts of 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. The rest of the time sensor nodes were in deep

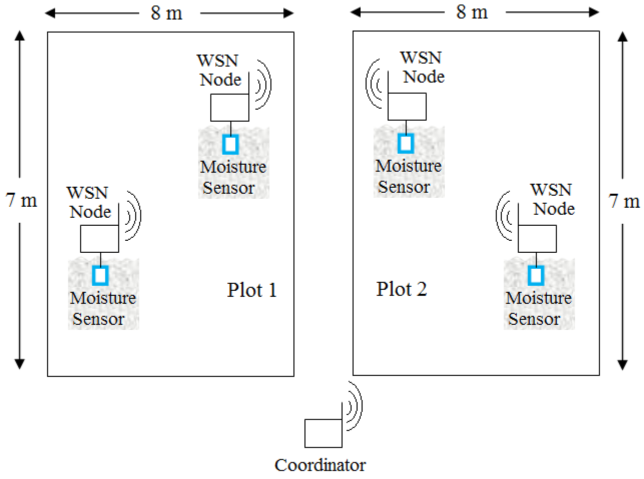

Fig. 2. Sensor location in the field.

sleep mode to conserve power. Once the measurements were done, the nodes sent the data via the XBee transceivers to the coordinator node where it was being aggregated.

### C. The Coordinator Node

As a coordinator node we used a Waspmote equipped with a ZigBee module. This component is the heart of the whole system and has several crucial roles to perform. Firstly, as the most capable node in the network, a ZigBee Coordinator (ZC) permits and sanctions all ZigBee End Devices (ZEDs) that are in quest of connecting to its network. That is, it is responsible for network formation by allocating 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 (B) above. The received sensor data included the Watermark frequency and the soil temperature. These were used to derive the soil moisture potential using two equations. The coordinator then had to make a decision on whether to irrigate or not depending on the level of the SMP. Four of the I/O pins of the Waspmote's microcontroller were connected to a latching circuit and were used to initiate or terminate the irrigation by sending corresponding pulses to them.

Finally, we used the ZC to relay the data to a gateway for forwarding to a remote server. When receiving data from the sensor nodes, which included watermark frequency and soil temperature, the coordinator was also capturing the Received Signal Strength Indicator (RSSI) of every packet it was receiving. 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 being aggregated and prepared in a special way to suit the characteristics of the SMS transmission system. Thereafter, the SMS data was relayed to the gateway for forwarding to a remote server. This was taking place every 15 minutes when irrigation was in progress or every 30 minutes when the irrigation system was in an idle mode.

### D. 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, the latching circuit allowed us to use a short pulse from Input/Output (I/O) pins of the coordinator's node. 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 (5.5W when latched); and the possibility of using a 12V DC power supply. The two latter features allowed us to use a single 14W, 12V 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 hard to source.

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 via 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.

### E. The Gateway Node

One of the four sensor nodes discussed in (B) assumed the role of a gateway to send data to a remote monitoring site via a cellular network. In addition to a ZigBee module, we equipped this particular Waspmote sensor 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. Then the sensed data was being sent to a coordinator for processing and aggregating with the other sensors' data. Afterwards, the coordinator was sending the 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.

We could have used the coordinator node to send data directly to a remote server by equipping it with a GPRS module, but we opted for this arrangement because of the following three confounding issues: Firstly, the coordinator was used 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 hence its battery was being extensively depleted. It was therefore necessary to offload SMS sending duties to a gateway node which otherwise was less loaded. Note that sending same data through ZigBee module consumes less power (2mW) than sending via GPRS to the cellular network (2000mW) [7].

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 mishaps directly to the personal mobile number of the management personnel.

Finally, this study revealed a very important practical trap about the conflict between the ZigBee module and the GPRS module. When both modules were powered up, the ZigBee module lost connection resulting in a total network failure which required manual reset. Nonetheless, using software at a gateway layer, we were able to turn OFF one module when the other was active. It was not possible to do this at the coordinator layer since the ZigBee module acting as ZC was always to be ON to avoid losing connection with the other network nodes.

## III. PERFORMANCE EVALUATION

In this study we evaluated the performance of the WSN for agricultural application. Firstly, we evaluated 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 investigating 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 Received Signal Strength Indicator (RSSI) with different distances and heights of the maize plants as parameters. Zennaro and others [8] 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 evaluated 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 [7]. This means that when RSSI goes below this value 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.2 shows sensor positions for this case).

Fig. 3 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. 4 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 less likely for the network to fail when the distance between the nodes and the coordinator was 7 m.

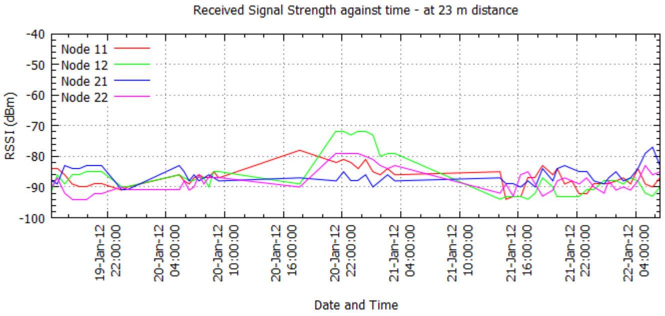

Fig. 3. Received Signal Strength against time - at 23 m distance.

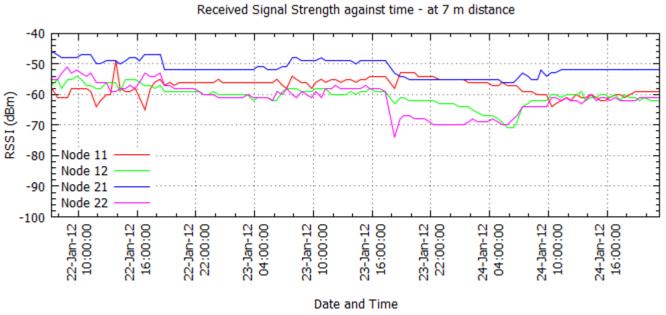

Fig. 4. Received Signal Strength against time - at 7 m distance.

It is therefore very important in any practical deployment to consider placing of sensor nodes in such a way that the distances between the nodes at the height of 60 cm are optimized in accordance with the size of the field.

Furthermore, we noted that the RSSI was not only a function of the distance but also other factors including multipath fading, which was exacerbated by the movement of wet leaves of the maize plants, play a very crucial role. This is portrayed by the wavy behaviour of the RSSI graphs.

*2) RSSI over Height of Plants:* 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. Fig. 5 shows a scenario in which the sensor is being fully covered by the maize plants.

Fig. 6 shows a pattern of RSSI as an average of all the individual nodes' RSSIs. The graph shows a slight decrement in the level of RSSI with time. Note that the crop height increased from 50 cm at the start of the experiment to about 200 cm thereby covering the in-field sensor nodes completely. However, as depicted by the best-fit line of the average RSSIs, there seems to be no major degradation in the quality of the communication link corresponding to the height of the plants.

Fig. 5. Sensor node being covered by maize plants.

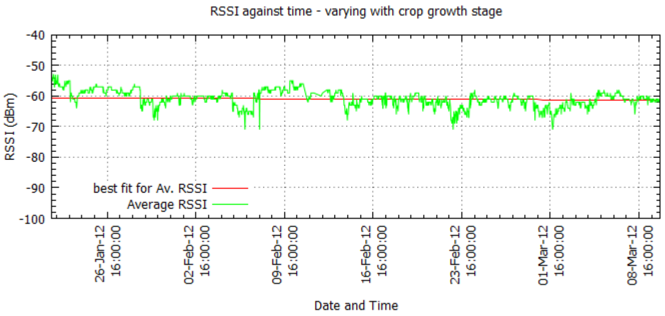

Fig. 6. RSSI varying with crop height.

## 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 the devices in this system. After evaluating the performance of the systems in terms of energy usage, we discovered that the four in-field sensor nodes which were using sleeping mode as a way of conserving energy were more efficient that the coordinator which was never put into sleeping mode. The gateway node also 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 small, 2.5W solar panels were enough for the three in-field sensor nodes while the gateway and coordinator had to be powered by a 5W and 7.5W solar panels respectively. We also changed the batteries of the gateway and coordinator from 1150mAh which were initially deployed in all the nodes to 2300mAh and 2450mAh respectively.

Fig. 7 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 made. The graphs in this Figure show that on a number of occasions 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 17 January and 23 January when there was no sun shine due to heavy rains. It was after this that the changes in the powering requirements for the gateway and the coordinator were inevitable.

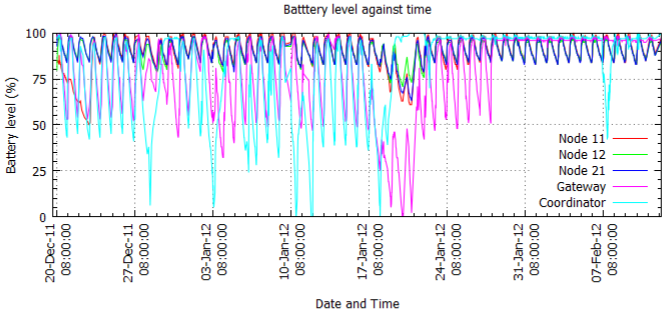

Fig. 7. Battery Levels against time.

## C. RSSI Vs Battery Level

It was also important to investigate the correlation between the two previously discussed performance metrics. Fig. 8 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 have a slump at around 4:00 PM. They start to peak again at around 7:00 AM when the sun rises and starts to charge batteries.

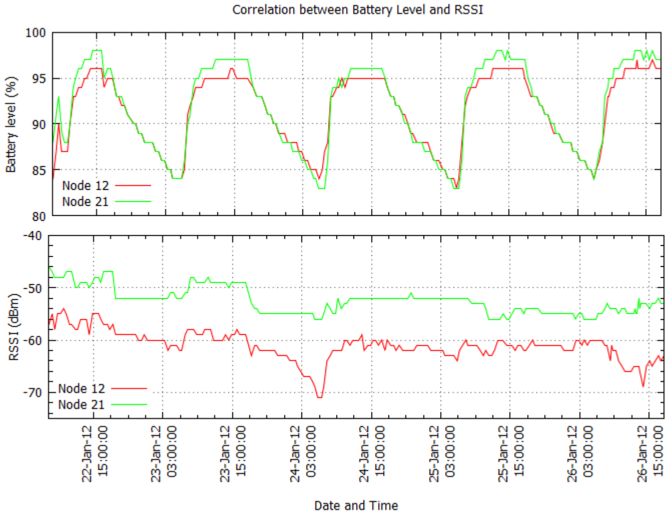

Fig. 8. Correlation between Battery Level and RSSI.

These results show a very interesting feature especially when considering the powering requirements and the required level of the 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 the RSSI and the expected lifetime of the batteries used in any WSN deployment. However, we noted that there were also other factors that affected the level of RSSI including multipath fading caused by the movement of wet leaves as well as the distance between the nodes as discussed previously.

## IV. CONCLUSION AND FUTURE WORK

In this paper, we have demonstrated how an Irrigation Management System 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 a serious impact on the robustness of WSN deployment since it directly erodes the 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 robustness of the system.

As future work, we propose large scale deployment to observe the impact on the role of the coordinator in handling numerous queries from the in-field sensors. Since WSNs are flexible on the software layer and, hence, they can accept any scheduling strategy, we further propose the future deployment to focus on the water application efficiency in order to reduce the energy used in irrigation water pumping. This will promote the installation of lower-capacity solar PV water pumping systems for irrigation to suit the socio economic conditions of small scale farmers in the developing world.

## ACKNOWLEDGMENT

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