Water Saving in Agriculture through the Use of Smart Irrigation System

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ABSTRACT

Conventional agricultural irrigation scheme currently in use is a major water consumer due to dissipation and drainage. It can result in over or under irrigation, which could have a negative impact on crop yield and quality. In this paper, we provide the architectural design and implementation of a smart irrigation system that uses a Wireless Sensor Network (WSN) based on Arduino and XBee technologies. The system monitors agricultural conditions and automatically controls the soil moisture level in the root zone to keep it within its optimal range. The implementation of the WSN is provided. A comparison of the amount of water consumed between the smart system and the conventional irrigation approach are discussed. Our results obtained using a pilot prototype indicates that a significant amount of water-saving can be obtained when using a smart irrigation system instead of the conventional approach. The complete code for this paper is available on Github at https://github.com/areen-naji/Wireless-Sensor-Network.

CCS CONCEPTS

• **Applied computing**; • **Computers in other domains**; • **Agriculture**; • **Additional Keywords and Phrases: Wireless Sensor Network, Smart Agriculture, Water Management, Xbee**;

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1 INTRODUCTION

Irrigated agriculture is one of the most important sectors of the economy worldwide. It supplies 40% of the world's food and it is the main consumer of fresh water. According to Food and Agriculture Organization (FAO), an average of 70% of the world water supply is consumed in irrigated agriculture [1]. In this agriculture, an irrigation system must supply water to the plant root zone at a rate sufficient to meet the plants' water needs without exceeding it. Excess water may cause the plants to grow slowly or not develop properly. Thus, drainage of excess water is required to maintain a healthy plant and an efficient irrigation schedule is crucial on crops' yield and water consumption. The consequence of under-irrigation is less yield and poor crops' quality. While, over-irrigation increases the amount of wasted water, the cost of pumping the extra water, environmental pollution due to the leaching of nutrients, and wasting extra medicine and fertilizers that is delivered to the plant through water [2].

Increasing the yield and the quality of the crop without degrading resources are the main objectives of any agricultural management system. It is estimated that 50% of the world population are still practicing traditional agriculture. In traditional agriculture, irrigation is scheduled solely based on the farmer's experience which is inefficient and wasteful. The result is an irrigation efficiency under 40% [1], which means there is a room for improvement. Irrigation efficiency depends on the type of irrigation. For instance, drip irrigation is more efficient compared to surface irrigation where significant amount of water is dissipated to drainage. It also depends on irrigation schedule, which determines the amount of water to be applied and the timing of application. There exist several techniques to schedule irrigation efficiently. Each technique has its own advantages and disadvantages [3]. In plant-based irrigation management, a controller uses micro sensors measurements of stem diameter and leaf thickness to schedule irrigation. This approach is still under research [4]. A popular scheduling method is based on the soil-water balance which is based on the estimation of crop evapotranspiration [5]. Another approach is based on analyzing images of the plant taken from satellite [6]. A more recent approach is based on the use of root-zone sensor to obtain soil moisture level and to maintain the moisture level between optimal values [7] [8] [10] [31] [33]. This method is simple and works for any kind of plant as long as the threshold level for the irrigation scheduler are correctly chosen. Multiple different sensors can be used to monitor various environmental conditions to be used in controlling the irrigation schedule. For example, in [32] the water schedule was based on data gathered from leaf wetness, soil moisture, and soil PH, and atmospheric pressure sensors. Other sensors are used to inform farmers about the chemical composition of the soil to help them choose the appropriate kind of fertilizers and to suggest the suitable crop for next season.

Until recently the application of the root-zone sensing for irrigation management was less popular compared to water balance method. However, advances in root-zone sensing technology and the falling of its cost makes it a promising choice. Sophisticated root zone sensors such as neutron probes are available. However, much cheaper and practical sensors are needed in large scale irrigation systems. Sensors based on the measurement of soil dielectric properties become popular and provide a low-cost alternative. The irrigation management system is also required to provide the means

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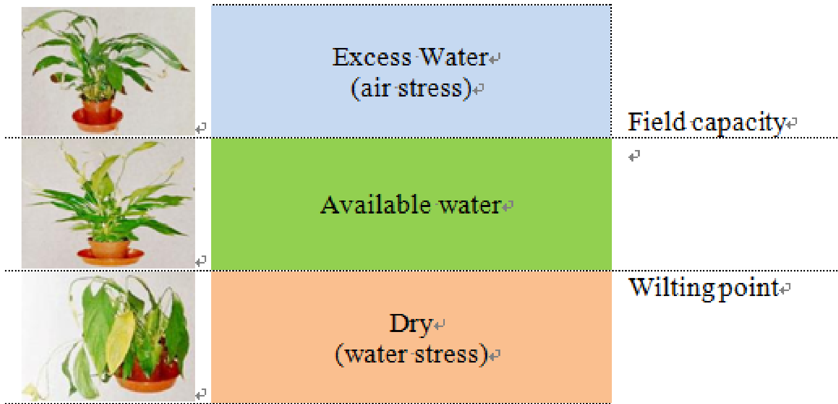

Figure 1: Optimal root zone moisture level

for measuring and controlling the flow of water. Consequently, improving irrigation efficiency by reducing wasted water, can have a significant saving of water in addition to other valuable resources.

To help achieve these goals, one approach is to establish new agricultural techniques that focus on productivity and managements of the available resources. The goal of such techniques is to increase the agricultural productivity [9] by increasing the yield and minimizing the cost and losses. One main component helps achieving these goals is the use of sensing and actuation technology communicated through a WSN in what is called Smart Farming systems [10, 11]. In these systems, several technologies include Cloud Computing [14], Wireless Sensors Network (WSN) [13], and the Internet of things (IoT) [12] are integrated together and to create an environment that advance productivity in agriculture.

In this paper, the design and implementation of a fully automated system that manages irrigation using WSN is provided. An array of low-cost moisture sensors is used to measure the soil moisture level in the root zone. Based on the moisture level, the system uses electric valves to control the irrigation in the field. The WSN developed in this paper uses the XBee radio modules which is based on ZigBee wireless communication standards. The Arduino microcontroller is used for processing.

The rest of the paper is organized as follows. In section 2, we describe the related work. In section 3, we present our architectural design of WSN based irrigation management system. The implementation of our system using IoT devices is described in section 4. section 5 provides our results and discussion.

2 METHOD AND MATERIAL

2.1 Root Zone Management

Monitoring and controlling the soil water-content in the plant root zone is necessary to maintain a growing healthy plant and improve agricultural productivity. The plant-water requirements depend on several factors include the plant kind, the age of the plant, and the texture of the soil [15]. Several mathematical models have been proposed to estimate the soil characteristic curve to calculate the water requirement for optimal irrigation schedule. In addition to optimal soil water content, optimal concentration of air is necessary [16]. The moisture level of the soil when all excess water has drained out due to the force of gravity is call field capacity [17, 18]. At this level, the soil has a balanced optimal concentration of water and air which provide an optimal condition for the growth of the plant. Shortage of air concentration due to excess water causes a condition called waterlogging, which can reduce the yield and harm the plant if stayed for a long period of time [18]. Also, excess of water cause losses in the water itself and other chemical that is delivered through water.

In contrast, shortage of water below a threshold value, called the wilting point, causes a condition called plant water stress. When this condition occurs, the plant can't pull water from the soil which causes the plant to wilt, and possibly die if stayed for a long period of time [17, 18]. Therefore, the ideal moisture level of the root zone should be maintained between these two threshold values, the field capacity and the wilting point. However, these values depend on the soil texture and the kind of growing plant. Figure 1 shows these cases.

Maintaining the root zone moisture in the ideal range is a challenge in conventional irrigation that requires an optimal scheduling. The system described in this paper provides the Wireless Sensor Network component of an automated system to maintain the root zone moisture at optimal value for a given crop and soil texture. This system helps improve the productivity of farming by decreasing the wasted resources such as water, nutrient and human labor while increasing the yield. The system uses state-of-art technologies which are described in the following sections.

2.2 Wireless Sensor Network

A Wireless Sensor Network (WSN) is a group of connected autonomous devices called nodes. The main function of a node is to gather data from connected sensory devices, perform limited processing on this data and transfer the processed data to a base station for further processing and sharing. Also, a node can trigger action in the environment through connected actuators. The availability of low-cost sensing devices, embedded microcontroller, and wireless communications enables the design of WSN that contain a large number of nodes. The architecture of a WSN consist of the following main components [19].

- 1 ***Wireless sensor nodes.*** Nodes in a WSN are deployed over a geographic area to collect environmental data. A wireless node has the capability to process the data gathered from the attached sensors and transmit it to a base station through wireless channels. The structure of a typical wireless sensor node consists of four basic components: 1) *Sensors*, a sensing unit consists of sensors and analog-to-digital converters (ADC) that converts the analog signals to digital signals, 2) *Microcontroller*, this unit can be programmed to perform certain local computation, 3) *A wireless communication unit*, the unit consists of a radio transceiver used to receive/send messages from/to the network, and 4) *Power unit*, this is a battery that powers all components of the sensor node.
- 2 ***A Gateway***. A gateway is a network element that connect two different-types of networks. It is basically a protocol translator. In a WSN, the gateway acts as a bridge between the wireless sensors network that uses a particular communication protocol such as ZigBee and the IP-based network.
- 3 ***A Base station***. The base station is a computer connected to a gateway. It runs an application that gathers the data from the sensor nodes, process it, and controls the environment by sending control signal to actuator to trigger tasks. The base station can act as a bridge between the wireless sensor network and an applications that runs on the cloud.
- 4 ***WSN Communication Protocols***. Wireless nodes are highly limited in power, computation, storage, and bandwidth. The design of a WSN takes these limitations into consideration. ZigBee is a recent technology that works on top of the IEEE standard 802.15.4 and supports mesh network topology. The main features of ZigBee is its low data rates, low power consumption, and low cost. Sensor nodes may be deployed in an ad hoc manner [20] or structured. A ZigBee node can be configured to be:
- •Coordinator: ZigBee networks have one coordinator node that is responsible on forming the network and managing addresses.
- •Router: A router node can send, receive or route information. The network may have zero or more router nodes.
- •End nodes: The network may contain one or more end nodes. End nodes can send or receive information, but they cannot rout it. They can save power by going into a sleep mode. End nodes require a router or the coordinator to be their parent to be able to join the network.

3 SYSTEM ARCHITECTURE

This section describes the architectural design of the proposed WSN-based application for smart farming and water management system. As shown in Figure 2, the land is divided into several irrigation units called "zones". Each zone is a unit of predefined area that present one management unit of the field. A zone should be selected so that it has uniform water requirement. This means that a zone should be planted with the same plant kind at the same time, so all the plants in a zone have the same age. Also, a zone should have a uniform soil texture and be flat. Consequently, the water requirement at every point in the zone are similar.

The irrigation of each zone can be started and stopped automatically using an electrical valve controlled by a controller program running on the base station. In each zone, one or more moisture sensors are distributed at different locations and different depth uniformly. Each moisture sensor is connected to the nearest wireless node and has an identifier. Wireless nodes read their attached sensors periodically and send their values to the controller that runs on the base station computer. Other sensors can be deployed to monitor other quantities such PH, pollution, and temperature. The base-station application computes the average moisture value of for each zone. This value represents the zone's moisture. Then, the application checks the moisture level of each zone whether it requires irrigation or not and sends a signal to the node that controls the irrigation valves.

Since a limited number of sensors can be connected to a node. Several wireless nodes are deployed in the field to accommodate all sensors.

In this paper, we provided a simple decision support system that decides when to start/stop the irrigation of each zone. For each zone an upper T_{upper} and a lower T_{lower} threshold values for the optimal moisture levels are set. These values should be set based on the plant kind, plant age, and the soil texture which they can be obtained from the agriculture literature. In the evaluation of this system, these values are preset by an expert farmer. The expert farmer examined the soil by his hands while measuring its moisture. Based on his recommendation, the moisture upper and lower threshold values are recorded. Then, in a timely manner, the average moisture value for each zone is calculated using all sensors readings in that zone. Then for each zone we close the water valve if the moisture level is greater than the upper threshold and we open it if the moisture level is below the lower threshold. If the moisture level is within the optimal range, the state of the valve will not be changed. The algorithm is shown below.

Algorithm 1 Irrigation decision

```
for each zone in zones, do
if M(zone)  < T_lower  (zone)                ; Irrigate the zone if its
Moisture is less than the lower threshold
    turnOnValve(zone)
   else if M(zone) > T_upper (zone)          ;  Stop if the zone's
Moisture is greater than upper threshold
                   turnOffValve(zone)
               endif
 end
```

4 IMPLEMENTATION

4.1 Hardware components

The main components of a Wireless Sensor Node are the microcontroller, radio frequency transceiver (RF), power source, and one or more sensors. There exist several technologies that can be used to implement these components. The difference between these technologies is in the cost, ease of use, and reliability which includes the

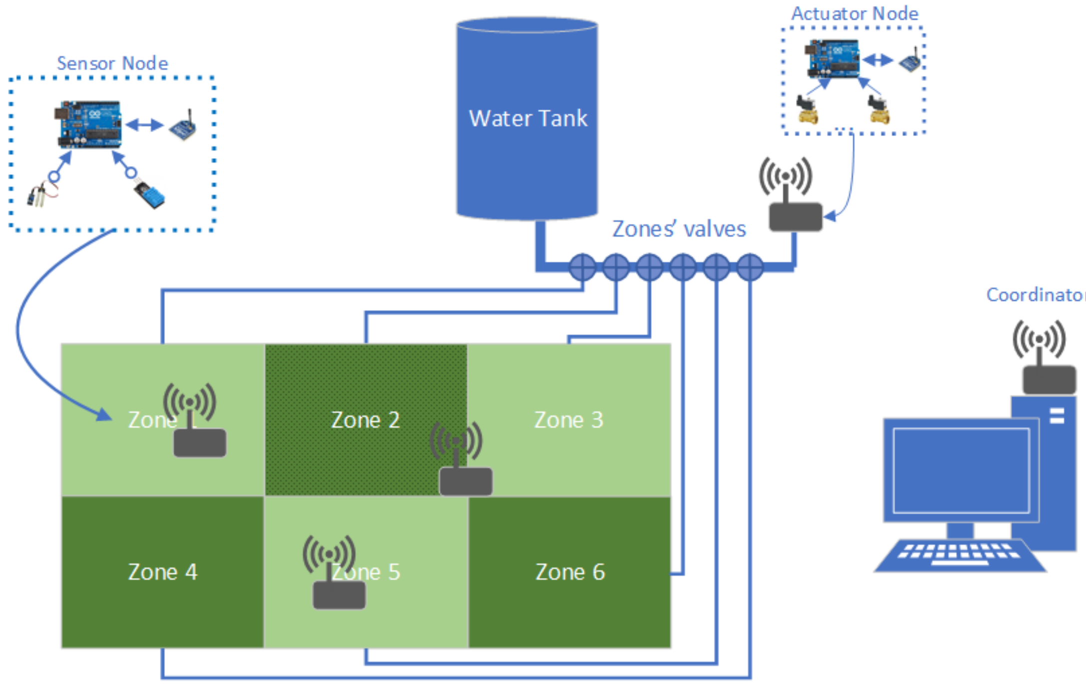

Figure 2: Smart Agricultural Irrigation Management System Architecture

Figure 3: Harware components

communication protocol stack that they support. In our implementation we used the XBee modules for the short-range low-power wireless communication and Arduino Uno for the microprocessor [21]. For the environment sensors, we used the moisture, temperature and humidity sensors. Other electronics parts such as shields and adapters are also used. Figure 3 shows these components and their descriptions is below.

- •***XBee Wireless Modules***. Xbee is a family of wireless modules that support a variety of communication protocols including Zigbee protocol. These modules are suitable for low-power short-range requirements of wireless device networking [26]. In this paper, we used the XBee series 2 that allows a WSN to form a network using auto-discovery and broadcast, and covers a large area which is suitable for agriculture application. XBee modules can communicate with each other in one of two modes, either in a transparent mode or in a packet-based Application Programming Interface (API) mode. All XBee communications in this paper are performed in API mode. One advantage in using the API mode is that it allows specifying message destination address at runtime. This allows software running on the base station to communicate with a particular node to accomplish a particular task dynamically at runtime. XBee key features include urban connectivity up to 100 m, low power, support analog-to-digital conversion, easy-to-use, source/destination addressing unicast & broadcast, and the support of peer-to-peer topologies.

- •***The Arduino microcontroller***. The Arduino is a programmable logic controller. It has 14 digital input/output pins, 6 analog inputs, USB connection, and a power jack.
- •***Soil moisture sensor***. We used the YL-69 soil moisture sensor [22]. The output voltage of the sensor is inversely proportional to the water content in the soil. When the soil is wet, the output voltage is low. The sensor has a built-in potentiometer for sensitivity adjustment of the output voltage. The sensor is connected to an analog input pin of the Arduino which has an ADC that produce a digital number in the range 0-1024.
- •***Solenoid water electrical valve***. A solenoid valve is an electromechanical device used for controlling water flow. The valve is controlled by electric current that can be open or close a water valve [23].
- •***Relay for Arduino***. A programmable electrical switch that we used to control the electrical valve by the Arduino. It acts as a bridge between the Arduino and high voltage devices [24].
- •Several adapters to connect the different parts of the wireless nodes. We used the XBee USB adapter to connect the Xbee radio to the computer USB for configuration and data communication. Also, we used the XBee Arduino Shield to provide an interfaces of the XBee with the Arduino.

4.2 Software libraries

The complete software implementation for this paper is available on githup [25]. The following are the main packages that we used in this implementation.

- •Python 3.3. The base station application is implemented using the python programming language.
- •Arduino Software: for Arduino uno microcontroller programming [28].
- •PySerial library. This package is used to connect the base station application with the Xbee coordinator module that was connected to the USB serial port [27].
- •Digi X-CTU. A desktop application used to configure the XBee modules using serial USB connection [29].
- •FTDI Drivers. Used for USB to Serial communications [30].

4.3 Implementation

In this section, we describe the implementation of the proposed system which includes, the implementation of the software application and the WSN implementation. As discussed in section 3, the wireless nodes has two types of functionality, the coordinator node and the end node. In the implementation of this paper, the coordinator node controls the electrical valves as well. However, wireless nodes must be configured before they can communicate with each other.

- 1) ***XBee radio configuration.*** Each XBee radio has internal microcontroller that runs a firmware. The firmware performs all its addressing, communication, security, and utility functions. A user can configure the firmware with different settings like its local address, type of security, and how it should read sensors connected to its local input pins. Any XBee module can be configured to be a coordinator or an end node. XCTU software is used to configure the Xbee addresses and the type of each node.
- 2) ***End-node implementation***. Figure 4 (left) shows the circuit diagram of a wireless sensor node. The Arduino is connected to the XBee radio module using the TX and RX bins. Three sensors are attached to each sensor node, the DHT Sensor to measure the temperature is connected to a digital bin, and the soil moisture sensor to measure the soil moisture is connected to an analog bin. The Arduino analog bins has a 10-bits ADC. The end-nodes remain sleep and wake up periodically to check for RF data. When they wake up, they send their attached sensors' readings.
- 3) ***Coordinator node***. The coordinator node is connected to a computer using USB explorer adapter. The pyserial library is used to implement the communication with the computer through the serial port. The XBee library is used to implement the communication with other nodes in the network. The coordinator node in this implementation acts as a gateway between the WSN and the outside world. Figure 4 (right), shows the coordinator node circuit diagram. It contains an XBee module configured to be the coordinator. In addition to the basic functionality of a coordinator node, the coordinator controls the electrical valves through a relay as shown in figure.
- 4) ***Base station controller***. The controller is a python application running on the base station computer. In a timely manner, the controller sends a request to the WSN inquiring for all sensors' readings and then listen to the serial port for response. The coordinator node receives the request from the serial port and broadcast it to all sensor nodes. In response to the request, sensor nodes wakes up from sleep reads the sensors' data from the attached sensors, assemble it into a packet and send it to the coordinator. The coordinator writes the packet to the serial port. Once the controller reads a response from the serial port, it extracts the sensors readings and their IDs from the packet. From the sensor ID, it identifies the zone and checks the moisture sensor reading and compares it with upper and lower thresholds. Based on the value of the zone's moisture and the upper and lower thresholds, the controller issue a request to open or close an electric zone's electric value.

5 RESULTS AND DISCUSSION

To evaluate the performance of the proposed system in terms of water saving and crop quality, we considered the farm model shown in Figure 5. In this model, the land is divided into two identical parts exposed to the same conditions. The left part was irrigated using traditional irrigation, while the right part was irrigated using the smart irrigation system.

Since the focus of this study is to evaluate the amount of water saving when using automatic irrigation, we set the upper and lower moisture level values based on the farmers experience. This allowed us to factor out the optimal choice of the threshold parameters and evaluate the water saving due to the automatic irrigation alone. The thresholds' values were set to 370 for the upper moisture threshold

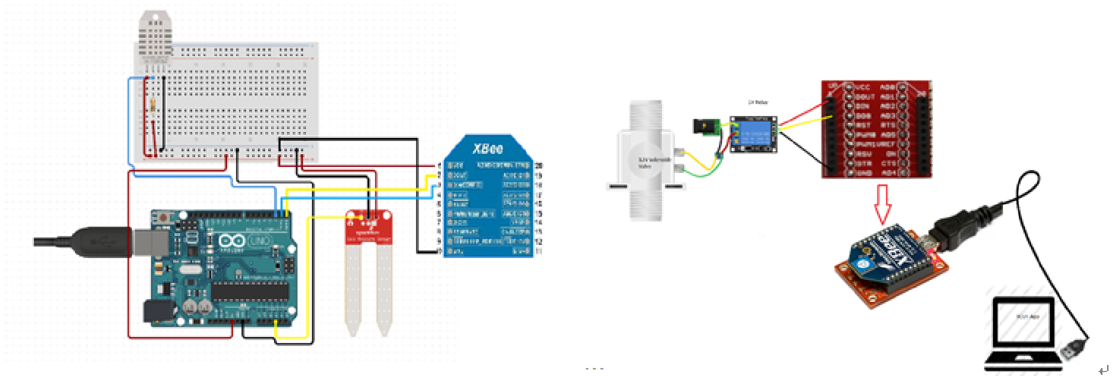

Figure 4: Wireless Sensor Node and coordinator node circuits.

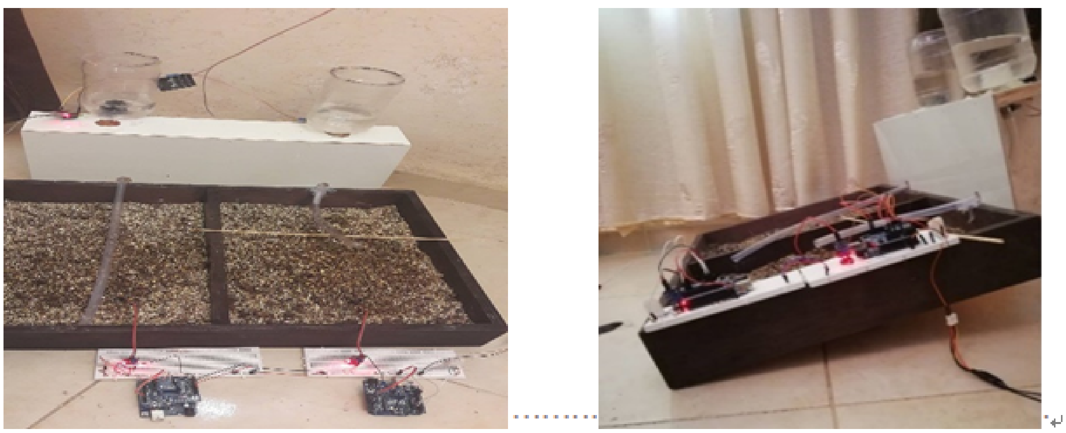

Figure 5: Farm model for the evaluation of the smart system. Flat farm model (left) and sloped model (right)

and 420 for the low moisture threshold. Notice that, the sensor reading is inversely proportional to the moisture value. Low moisture corresponds to high sensor reading and vice versa. The lower value is the average values of the moisture sensor readings when the experienced farmer thinks that the plant should be irrigated. The upper value is the average values of the moisture sensor readings when the farmer thinks that the soil is moist enough and irrigation should be stopped. It is possible to calibrate these values to the moisture units, but that is not necessary since the actual moisture values are not required. The upper and lower thresholds can be set dynamically as a function of the age of the plant and other parameters, but we didn't consider this enhancement in this study.

5.1 Flat Land

For this study we planted barley, because of its rapid growth, and stable and high moisture requirements. The conducted experiment took ten days long. For the traditionally irrigated part, we set the irrigation schedule daily. In typical traditional farming the schedule is usually longer than that. For one day we monitored the moisture value for every minute. Figure 6 (left) shows the moisture values for one day where sensor reading is taken every minute. The smart system uses the moisture value to changes or maintain the state of the irrigation valve to keep the moisture level in the ideal range between the two thresholds. Figure 6 (right) shows the moisture values for four days where the moisture reading is taken every three minutes and the smart system changes the state of the irrigation valve as required to maintain the root-zone moisture in the ideal range. In the figure, the blue line represents the root-zone moisture level for the part that was irrigated using traditional irrigation approach, while the red line represents the moisture level values for the part that was irrigated automatically using the smart system. Long time period causes the moisture level in the root zone to go off the limits of the ideal moisture level and consequently increases wasted water, medicine, and nutrient. Short time period causes the wireless sensor nodes to consume more power.

As the figure shows, the moisture level is low (sensor reading is high) just before the irrigation started. Then the soil moisture increases rapidly (sensor reading drops) when the farmer or the automatic system opens the valve. After that, the sensor readings increase slowly and became dry by the end of day in case of the traditional irrigation. In case of automatic irrigation, the sensor reading increases (moisture decreases) until it reaches the upper

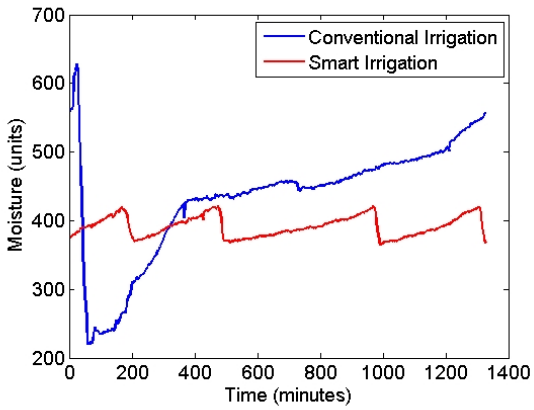

Figure 6: Traditional and smart irrigation. (left) one day experiment (right) five days.

threshold of 420. At this value, the system opens the electrical valve and irrigation started and the reading decrease until 370. At this valve, smart system closes the valve and the sensor reading start to increase again. This cycle is repeated continuously. As a result, it is clear that the variation in moisture in case of the traditional system is much larger compared to the automatic system, where the moisture is stable in ideal range.

We evaluated the amount of consumed water in each part for 4 days. The traditionally irrigation part consumed 5.6 litters while the automatically irrigated part consumed 5.28 litters. This means that using the smart irrigation system saves around 6% of water for this small farm model.

5.2 Sloping land

The efficiency of the smart irrigation system will increase if the irrigation area has a sloping ground or if part of the ground is exposed to the sun. In the flat ground all areas have equal water requirement and they lose water at the same rate. However, in the sloped ground, the higher areas lose water to drainage at a higher rate compared to low ground. In traditional irrigation system, every time the farmer opens the valves, it will irrigate all the land with the same amount. Consequently, water will drain down from the high area to the low area which can results in underirrigation in the high land and overirrigation in the low parts of the land. In the smart irrigation system every part of the land irrigated frequently and drainage will not occur from the high land to low land. The result is that all the land will have the same moisture level.

To evaluate the performance of the smart system compared to the traditional approach in this case, we tilted the land model as shown in Figure 5. Then, we placed two sensor nodes in the upper halves of the model and two in the lower halves. The left part is irrigated once a day similar to traditional irrigation and the right side is irrigated using the smart system. The upper and lower thresholds were set to 370 and 420 as before. The right part is divided into two zones where each zone is irrigated using a separate valve. In this experiment, we didn't plant anything and the experiment was conducted in one day long only.

The readings from the four sensors were taken every three minutes during the interval 16:00:16 to 20:30:16 and shown in Figure 7. Figure 7 (left), shows the moisture values of the upper and the lower sections of the part that was irrigated using the smart system. As the figure shows, the upper and the lower sections have stable and controlled moisture values between the upper and the lower thresholds. However, the upper section dried and required irrigation a little bit earlier than the lower part as expected. On the other hand, in the traditional system as Figure 7 (right) shows, the moisture values have a much larger differences between the upper and lower sections. Note that, these readings were started at the irrigation time for the traditional system. Also, as the figure shows the moisture value of the lower section (blue line) continued to increase (sensor reading decrease) after the upper section start to dry due to drainage. Also, the lower section is drying at a lower rate compared to the upper section which means that the upper section will be drier than the lower section at the next irrigation time.

The traditional system consumed an average of 87.5 milliliters/hour, while the automatic system consumed an average of 63.3 milliliters/hour. This difference shows a large water saving, because when it is measured for long intervals of time, and bigger ground spaces, the difference between systems would be larger.

6 CONCLUSION

In this paper, we implemented a WSN for smart irrigation system using state-of-art electric components. The system automatically maintained the root-zone moisture values between a preset upper and lower thresholds. The system uses moisture sensors for sensing the soil moisture, Arduino microcontroller and XBee radio modules for communications. A comparison between the traditional and the smart system irrigation on a farm model indicates that: 1) the smart system has better soil moisture stability at the root-zone, 2) the smart system reduces the wasted water, and 3) the smart system shows better stability and water saving in case of a sloped grounds. The smart irrigation system is planned to be integrated

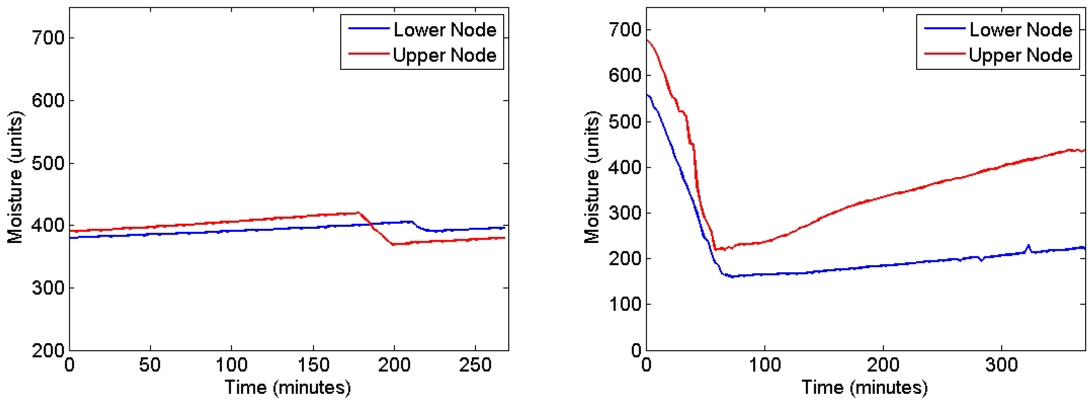

Figure 7: Automatic sloped land (left) and traditional sloped land (right)

with a cloud-based application to manage the data gathered by the sensors in the WSN for smart farming and water management.

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