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Agrinex: A low-cost wireless mesh-based smart irrigation system

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ABSTRACT

Wireless Sensor Networks in precision agriculture utilize natural resources more efficiently by collecting real-time data on farms to assist agriculture farmers to make intelligent decisions. Using this technology, farmers can effectively use the information to achieve greater yields and earn higher profits. This work presents an alternative to existing monitoring methods in the agricultural lands whilst providing an irrigation mechanism to help in resource conservation efforts by the use of a Wireless Sensor and Actuator Network (WSAN). Agrinex system features a mesh-like configuration of in-field nodes that act both as the sensor for soil moisture, temperature and humidity and actuator on a valve that regulates drip irrigation. The mesh-based network is dynamically design to allow self-reorganization of sensor nodes when changes happen in the network. The resulting Agrinex system is a promising start for a WSAN framework of various applications particularly in agriculture.

1. Introduction

Smart farming and precision agriculture involve the integration of advanced technologies into existing farming practices in order to increase production efficiency and the quality of agricultural products. As an added benefit, these technologies also improve the quality of life for farm workers by reducing heavy labor and tedious tasks [1]. Internet of Things (IoT) and Wireless Sensor Networks (WSN) in precision agriculture utilize the natural resources more efficiently by collecting real-time data on crop development, soil, weather, and air quality, to assist agriculture workers and farmers to make intelligent decisions with regards to planting, fertilizing, and harvesting crops. Using these technologies, farmers can effectively use information to achieve greater yields and therefore earn higher profits.

Despite being termed as an agricultural country for decades, Philippines have not fully utilized and explored the full capabilities and benefits of a modern agricultural monitoring system. The methods for gathering information regarding the vast Philippine agricultural lands had, until fairly recently, been done manually which are far behind the advanced and dynamic systems used abroad. A modern field data acquisition system that provides more efficient management of agricultural processes and an automated irrigation system that responds based on data gathered will greatly aid in land utilization as they will be kept at optimal conditions for higher productivity. One way this system can be realized is by the application of a Wireless Sensor and Actuator Network (WSAN) shown in Fig. 1.

WSAN is an integrated network of sensor nodes that transmits information acquired from sensors, actuator nodes that actuates to influence the sensed situation based on the data from the sensors and a sink node that collects data from the other nodes and uploads them to a remote server. For an agricultural setting, sensor nodes can measure temperature, soil moisture and humidity values and actuator nodes provide actuation for existing irrigation systems. The design of WSAN is recommended to be a mesh-like network as shown in Fig. 1 due to its advantages such no single point of failure in this case therefore it is a most reliable communication network structure, this is a more scalable network, and an alternate path is always present for the nodes so chances of data loss are low.

A WSAN is composed of sensor nodes capable of acquiring information and transmitting it to a sink node. For an agricultural WSAN, soil moisture, temperature and water level can be measured. The sink node collects all the data from various sensor nodes and sends it to a server for access to the information. The system decides, based on the data, when to actuate the actuator nodes that will influence the environment. The same sink node sends this signal to the actuator nodes. In this work, the actuator nodes provides

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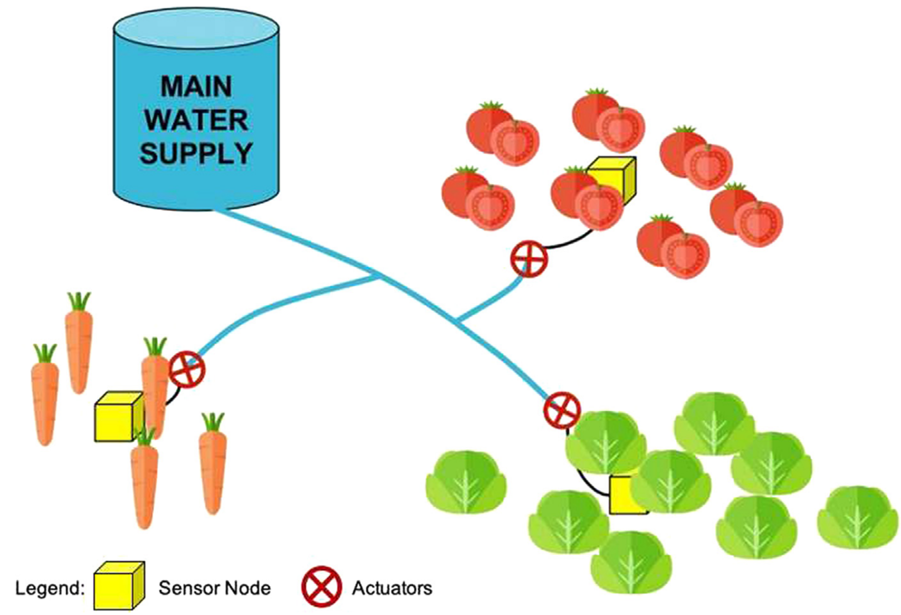


Fig. 1. Mesh-based Wireless Sensor and Actuator Network (WSAN) in smart irrigation systems for precision agriculture.

automation for a drip irrigation system. A drip irrigation system is a network of pipes or tubes that allows water to slowly drip directly to the soil for water conservation.

Some of the existing systems highlighting the benefits brought about smart agricultural systems as compared to their traditional agricultural methods are discussed below.

Data from an automatic irrigation system developed in Spain show that water can be conserved significantly by up to 30–60% because of the automated irrigation [2]. Another study that aims to protect potato from a fungal disease concluded that the disease is closely linked with humidity and temperature thus precise monitoring of the crop's environment allows them to know when and where to apply fungicide [3]. A WSN applied on a grape vineyard, also found that the use of wireless monitoring systems are less expensive and less labor intensive compared to its wired counterparts [4]. An innovative multi-agent system (MAS) composed of various subsystems of agents grouped by similarity in their tasks was developed to manage the information captured from WSNs for knowledge discovery and decision making in rural environments on actuator networks [5].

Moreover, a framework for smart data acquisition in precision agriculture that relies on the IEEE 1451 family of standards, which addresses the transducer-to-network interoperability issues was developed by another work. The framework includes a ZigBee end device (sMPWiNodeZ), as an IEEE 1451 WTIM (Wireless Transducer Interface Module), and an IEEE 1451 NCAP (Network Capable Application Processor) that acts as gateway to an information service provider and WSN (Wireless Sensor Network) coordinator. IEEE 1451 system architecture was proposed and its benefits in precision agriculture and closes with results/lessons learned from in-field trials towards smarter WSN [6]. Another work developed an innovative solution to the limited energy availability design problem by utilizing the ambient solar energy harvesting for battery charging of WSN nodes for smart agricultural monitoring. Despite the many challenges in solar energy harvesting like intermittency of available power, solar energy prediction, thermal issues, solar panel conversion efficiency, and other environmental issues, the system was able to maximize the WSN network lifetime using solar energy harvesting technique [7].

Other current solutions on smart and precision irrigation focused on developing mesh-based WSAN architectures and combining it with other technologies. A design and development of a self organizing and fault tolerant ad hoc multi-hop WSN for precision irrigation using low cost commercially available electronic components was developed. This includes the design and development of hardware units for sensor nodes to be deployed in the field for the measurement of soil humidity and a centralized base station to collect the information from the nodes and make decisions on irrigating. A reliable multi-hop WSN system with ad hoc routing algorithm for prolonged lifetime and fault tolerance has been developed and demonstrated using field trials and lab level simulations [8]. On the other hand, Smart Irrigation Systems (SIS) is a model wherein the large cultivated area is divided into several plots, where each plot has an independently automatic irrigation system. Its WSN is designed from a master node functioned as coordinator and three slave nodes using star topology [9]. Another study presented the reception of the collected data on the main control unit, designed on the Waspmote microcontroller platform equipped with XBee S2 coordinator. All necessary steps required to establish the communication between Waspmote platform and XBee S2 coordinator device are described, even though Waspmote platform is designed to communicate only with Xbee routers and end devices. Proposed architecture allows flexible implementation with reliable data transfer that provides necessary information for autonomous decision-making in smart irrigation system [10].

A modular architecture was developed using a WSAN component, a cloud platform component, and a user application component. A cluster tree topology was used as a simple protocol implementation for WSAN. Network nodes are organized on a cluster-tree topology, due to its high scalability, good energy efficiency, as well as reliability. Compared to the cluster-tree topology, the star topology does not provide good scalability [11]. Smart Irrigation Decision Support (SIDS) aims to measure the agricultural parameters including the soil temperature and soil moisture using the sensor nodes. The rate of soil moisture reduction is calculated from the current soil moisture reading and the previous one. These soil temperate and the rate of soil moisture reduction are employed as input parameters for fuzzy logic controller to produce the amount of irrigation time as output parameter [12]. Another study suggested algorithms to suboptimally restore the orphaned nodes to the network, satisfying network constraints for small and large areas of farming using WSN. It is proposed that optimal restoration can be achieved by finding the optimal parent node for each orphaned node that improves irrigation management [13].

The state of the art locally is not that far behind. Advanced Science and Technology Institute (ASTI) and Philippine Rice Research Institute (PhilRice) developed a Field Monitoring Station (FMON) which acquires environmental information such as soil moisture, leaf wetness, ground water level pressure sensor among others. Data is uploaded in a database for agricultural research studies and crop production information [14]. Another local study developed and implemented a smart hydroponics system that automates the growing process of the crops using Bayesian Network model. Sensors and actuators are installed to monitor and control the parameters of the farm such as light intensity, pH, electrical conductivity, water temperature, and relative humidity. The sensor values gathered are used in the building the Bayesian Network, which classifies and predicts the optimum value in each actuator to autonomously control the hydroponics farm [15].

Aside from this, PhilRice in partnership with the Information Systems Division and Climate Change Center developed a smartphone application called the "Agridoc" that features links to farming information, a journal for logging farming activities and farm management tools. This mobile application is connected to several in-field sensors such as water level sensor, paddy temperature sensor and a field weather station. This work aims to make these information accessible anywhere where there is Internet access [16].

Indeed, real-time agricultural environmental data is significant not only for research but also for precise application of water and pesticides. But developments only go as far as automated data gathering, processing and uploading information to the cloud for remote access. Most of these systems utilized either wired or wireless network but do not consider a wireless mesh-based network capable of adapting to changes such as adding and subtracting nodes to or from the network. Adding and subtracting of sensor nodes refers to the scalability of the network architecture. For smart and precision agriculture, it is very important to consider the possible future changes in the physical farm in terms of the geographical area of monitoring, the type of agricultural crop, variability of water sources, and/or weather conditions. Thus, the design of the network should be scalable and adaptive enough to this changes. The mesh-based WSAN is a good candidate as it allows the sensor nodes to connect directly, dynamically and non-hierarchically to as many other sensor nodes as possible and cooperate with one another to efficiently route data from/to base station. This work intends to solve this gap in the state-of-the art technologies in smart irrigation systems.

The main contribution of this work is the implementation of the mesh-based WSAN as a alternative approach in collecting and measuring physical parameters from the environment particularly in smart irrigation systems. The mesh network is designed as dynamic and supports adding and subtracting of sensor nodes by allowing reorganizations. This makes the system scalable and adaptable to changes in the network.

2. The Agrinex system

Agrinex is derived from agriculture and nexus, meaning a network. Fig. 2 shows the Agrinex system components. Agrinex is an agricultural WSAN with the following capabilities:

- Multiple sensors - The nodes deployed in the field gather data based on identified metrics: soil moisture, temperature and humidity. A single node is designed to accommodate different sensors.
- Drip irrigation as actuation - The drip irrigation mechanism was utilized for feasibility reasons as water conserved was adequately measured and installation of the system was within the time frame of the study.
- Dynamic mesh network - In-field nodes were configured in a mesh-like network. Their integration supports addition and subtraction of nodes and allows reorganization of the network on any instance of the two events.

A web application was developed for remote access and control of the network. It has the following features:

- Data visualization - Data gathered continuously were presented in real-time graphs. The volume of water dispensed for every actuation was also presented.
- Node status - Connectivity and threshold information can be viewed.
- User programmable - The option to modify threshold value to consider different condition requirements was given in the application.

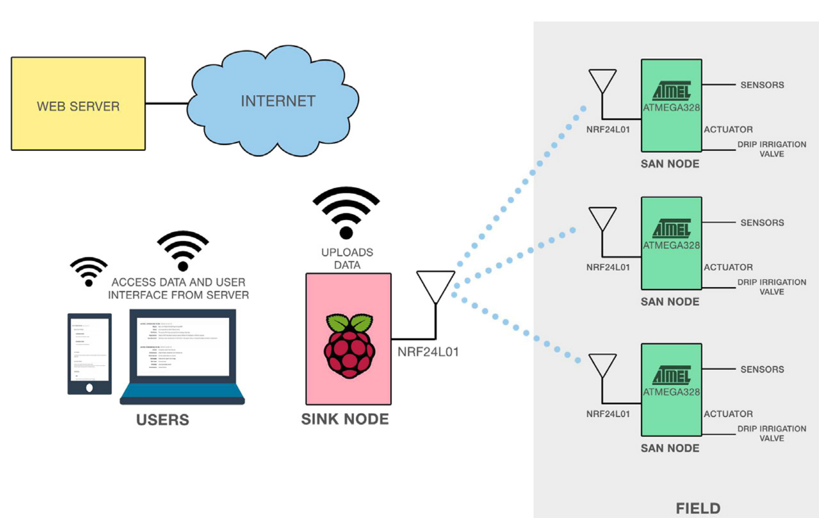


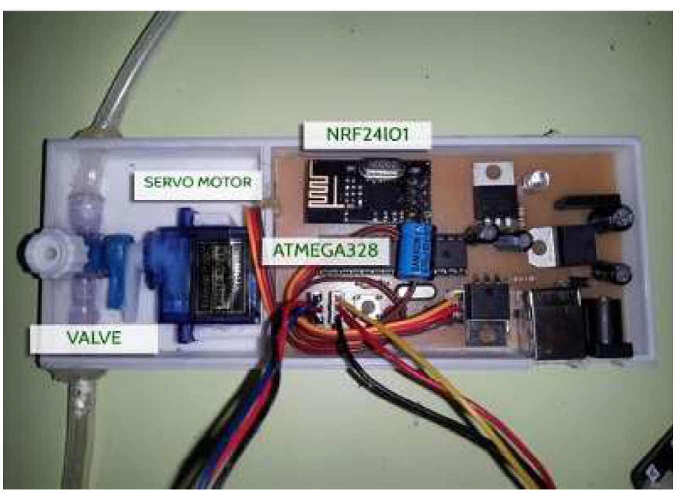
Fig. 2. Overview of the Agrinex system.

2.1. Sensor and actuator node

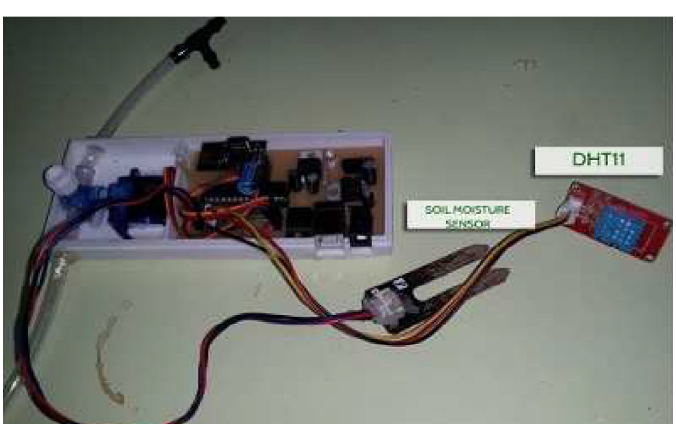
The Sensor and Actuator Node (SAN) is the in-field node that acted both as the sensor and actuator node. The two were integrated in the single module since actuation is needed in the exact location of the sensor. Using a single node for the sensor and actuator saves power and time because decision making for the node becomes local.

The SAN used an ATMega328 microcontroller programmed using an Arduino development board. Sensors include soil moisture sensor (DFRobot) and temperature and humidity sensor (DHT11). This node communicates using a low-power transceiver nRF24L01 that operates on the 2.4 GHz ISM band. Existing RF24 libraries [17] were used for the transceiver communication and mesh networking. The actual sensor node is shown in Fig. 3. Fig. 3a shows how the processing and wireless module components are deployed inside the node package. On the other hand, Fig. 3b shows the actual sensors used by the system to collect data from the environment.

The actuator for the irrigation used a servo motor and a valve. These two components were integrated together for an electronically-operated valve. Using the rectifier IRF530, the valve is ensured not to draw power when not in use. This module required two output pins from the microcontroller; One pin for enabling the module, and another pin for sending PWM signal to the servo. The actuator underwent leakage and functionality tests to verify this improvised electric valve setup operated by the servo motor.



(a) Processing and transmission components



(b) Sensor components

Fig. 3. Actual sensor node.

Fig. 4 shows the configuration of the sensor and actuator node. Threshold value needed to initiate actuation is stored in the microcontroller's EEPROM. This value can change upon instructions from the user. Fig. 5 shows the sensor node board schematic diagram. It shows the input sensor to microcomputer ATMEGA328P, DHT11 for temperature and humidity, and SEN0114 for soil moisture. On the other hand, the servo motor as output to microcomputer. Voltage regulation was provided to ensure constant supply to processing.

2.1.1. Sink node

The sink node was developed using a Raspberry Pi - a single board computer. This node used the same low-power transceiver (nRF24L01) to communicate with other nodes and its own Wi-Fi capability to communicate with the server. The sink consumes the most power so the node was plugged directly for a reliable power source. It was designed to collate information from the nodes, keep a local database of the information and upload them to the server. SQLite3 was used for the local database. It also receives instructions from the user regarding the changes on threshold values and sends them to indicated nodes.

2.2. Server and web application

The server communicates over a Wi-Fi connection. The server component of the system encompasses the online database and the user interface of the web application. Its back-end used Firebase, a web hosting site that features a real time database that is nonSQL. The frond-end of the application features data visualization of information from sensors, history of actuations, node information and user interface for node control. jQuery and Highcharts library were utilized for the website.

2.3. Network configuration

The network of the system allows self-organizing of nodes. Also, the network is self-healing. Any instance of an addition or subtraction of a node was handled efficiently by rerouting of the paths of the nodes towards the sink.

The libraries RF24 and RF24Network for NRF24l01 [17] were used for the network. RF24Network provides a system that automatically routes payloads based on the address assigned to a node. To have a mesh-like configuration, a protocol was developed where the node would send request messages to possible addresses in the network and when another replies with an available address, the former would restart with the address it received. An acceptance message will be sent back to the latter which will become the parent of the node.

Each node ensures that its children are still connected to the network by pings done at 3-min interval. When a child does not reply for three consecutive times it will be deleted from its list of active children to free up the slot for other nodes. Simultaneously a child node pings its parent in the same interval and frequency. If the parent is no longer available, it finds another parent using the protocol previously described and shown in Figs. 6 and 7.

2.4. Sensor and actuator node configuration

After network setup and sensor calibration, the node will start sensing and sending data to the sink every 15 min. Data sent to sink includes soil moisture, temperature, humidity and duration of actuation if it has occurred in the last 15 min. The sink sends

Fig. 4. Sensor and actuator node configuration.

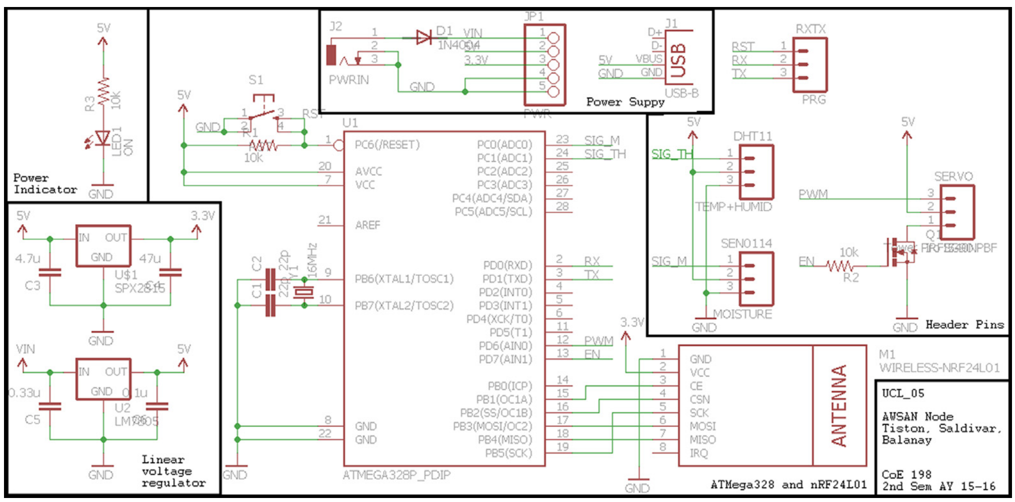


Fig. 5. Sensor node board schematic diagram.

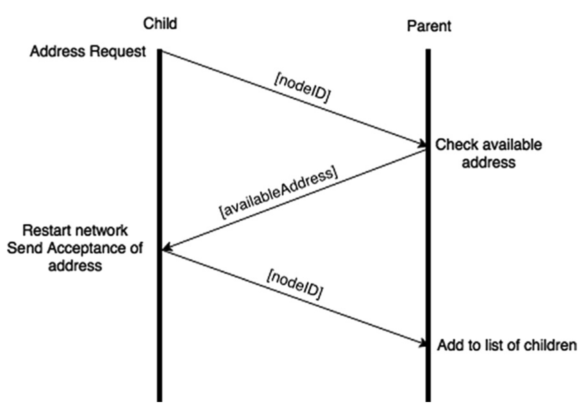


Fig. 6. Address request handshake.

back an ACK which contains the updated threshold for that node. If no ACK was received within a minute the packet will be resent. After the third try and no ACK was received the node will proceed to find another parent and resend the previous payload.

If soil moisture goes below the threshold, the servo motor would open the drip irrigation valve. To ensure that appropriate soil moisture is reached, a 10-s countdown is set after valve is opened and can only be closed after that time has lapsed and ideal soil moisture value is reached.

The node constantly checks if packets are available for itself. Packets can either be data packets, ACK, address requests, available address response, address acceptance, or pings. They are appropriately handled based on the packet header.

2.5. Sink operation

Two scripts run in the sink node. The first receives data from the nodes and stores it in specified the local database. It then sends threshold value updates to the nodes. It also tracks which nodes are still active. A node is active if it has sent data for the past 30 min.

The second posts data from node tables of the database to the cloud database (Firebase) using HTTP requests. It also updates the threshold tables of the local database from the data acquired from cloud database.

The two scripts communicate with each other to determine when to update either the cloud or local database. To ensure no redundant data was saved to the database each packet time stamp were checked before being written in the database. The communication between the microcomputer-based sink node and cloud server is shown in Figs. 8 and 9.

3. Performance evaluation and results

The experimental setup tried to be as close to what an open agricultural field is as possible. After the successful integration of the different nodes together with the server in close proximity inside the laboratory, the nodes were placed in systematic distances apart from each other in the field setup.

3.1. Range between sink and node

Wide agricultural lands require long range transceivers. To test the range of the nRF24L01, a range test was conducted to measure

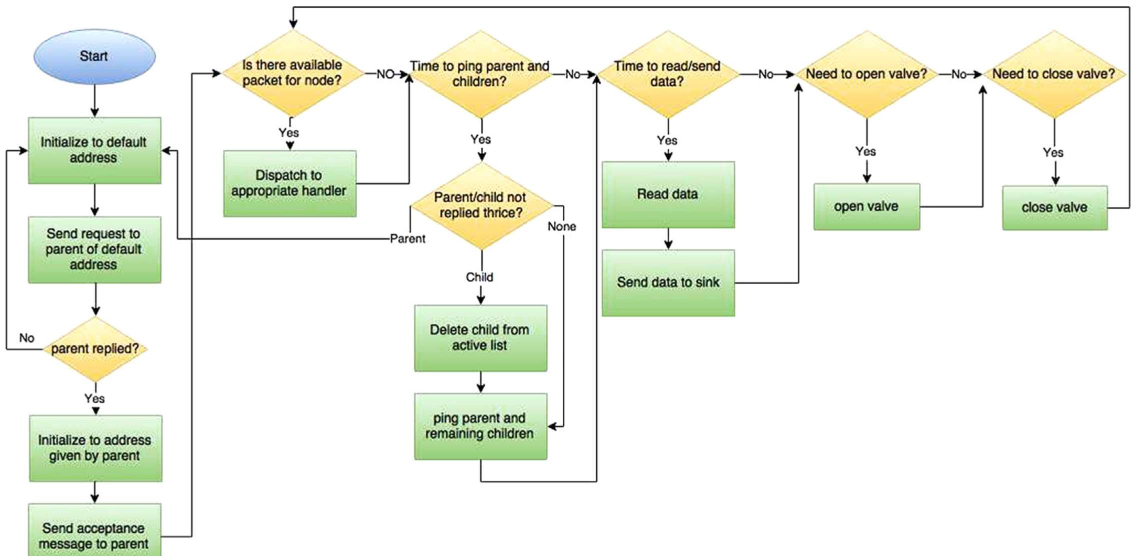


Fig. 7. Network communication between parent and child nodes.

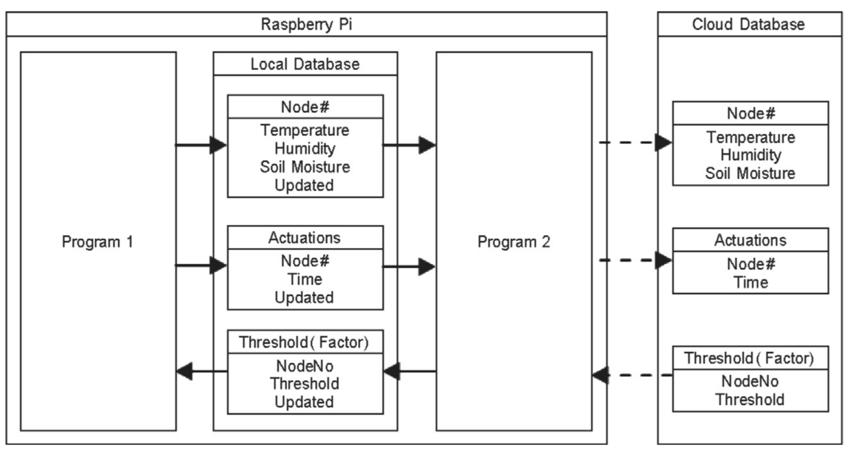


Fig. 8. Data flow between the sink node and cloud server.

distances where nodes can have stable connections. Initial results show that the sink and another node on a flat ground can only achieve perfect stability at around 3 meter range. Raising one node higher than the other as shown in Fig. 10, improved results.

3.2. Range between two nodes

A test was conducted to measure the maximum range between two nodes. From this test, raising the height was proved to be effective again in establishing connection. However, raising the height further makes it possible for the node to reroute its connection to the sink rather than to the nearer node. The success rate decreases as the distance between the two nodes increases. Table 1 shows the summary of range test results between sink and node as well as node to node. It can be observed that 90% success transmission rate was achieved at 11 meters for both sink-node and node–node communication. However, horizontal distance further than 11 meters again made connections unstable.

3.3. Delay

Duration measured was from sending a ping until a reply was received. For 1-hop node setup, average delay is 1031.58 ms and a 2-hop setup has 2062.26 ms. Different distances yielded difference of 1 to 3 ms. Additional hops follow this trend.

The delay from receiving a request from a node until an address acceptance message is received as shown in Fig. 6 has an average delay of 91.21 ms.

3.4. Power consumption

The power consumed for the node operation was observed in the laboratory. During transmission, the node has a power consumption of around 0.4 Watts otherwise it only consumes around 0.25 Watt. When opening or closing the valve, its power consumption is around 2 Watts. This valve operation lasts for about 500 ms. The node irrigates once a day based on the field test deployment that will be discussed after this. Based on computations, the node's power rating is about 0.4 Watts. The 5 V temporary power source used has a capacity of 13000 mAh or 65 Watt-hour. Theoretically, the node is expected to live 162.5 h or 6.77 days for a similar setup if the same power source will be used.

Theoretical results were proved to be close to accurate as the temporary power source provided power for the in-field nodes during the six-day field test presented in the next subsection.

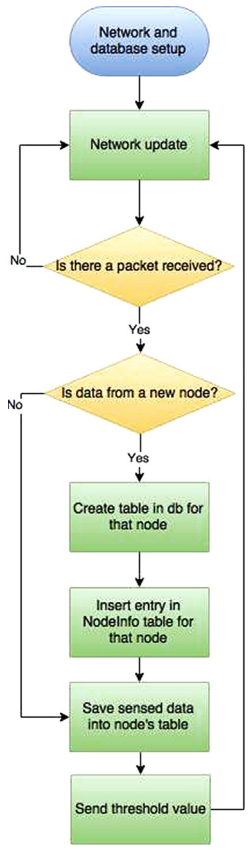


Fig. 9. Sink and node communication and database modification.

3.5. 6-day Field test

A six-day field test was conducted to observe the system's operation for a long period of time and for multiple network hops from the sink. The sink node was situated indoor for the power source but overlooks the wide open area of the field setup to be in the range of the SANs.

The nodes were placed within range of the sink and each other based on the range tests conducted. In cases when a node died, its children found another node to route its packets to. To ensure that the network would organize in a more than one hop setup, the sink was restricted to have only two direct child nodes.

Table 1
Range Test Result Between Sink-Node and Node–Node

Distance (Case)	Success rate(%)
5 m (A)	98.33
7 m (B)	98.00
9 m (C)	97.50
11 m (D)	90.00

Water supply for the irrigation was improvised. The ease of use of drip irrigation allowed use of household items for the improvised water supply. Two kinds of plants were used on two setups: both plants planted on the soil directly and both plants planted on a plant box. Apart from the installed drip irrigation, there was also a control setup for the traditional irrigation.

Fig. 11 shows the data gathered from one of the nodes. It is observed that around noon time, temperature values are at their peak and humidity values at their lowest. At this time, a significant decrease in soil moisture is also noticeable. This observation agrees with real field conditions. The interrupt in the soil moisture values account for the time when the node was temporarily disconnected from the network.

Fig. 12 shows that the actuation mechanism worked as expected. The threshold was initially assigned a lower value to avoid unwanted actuation upon deployment. The moment the threshold was set at 700, the system actuated and then stopped when the value was reached.

The use of drip irrigation proved to be significantly efficient based on the test. A decline in soil moisture ranges from 20–30 (plant box setup) and 30–70 (field setup) per day. To address the decrease, the actuator turns the water valve to compensate. When compared to the control setup, the 30–60% of water conserved using an automated irrigation was observed similar to the results from a similar study [2]. The system even exceeded this data when the water conserved reached 81%.

3.6. Web user application interface and usability

Fig. 13 shows the web-based application user interface of the WSAN-based smart irrigation system. The web application is composed of page options such as node summary, sensor readings, water consumption, and general information about the system. The node summary page provides the real-time monitoring of each sensor reading as shown in Fig. 13a. Each sensor reading can viewed on another page, the sensor reading page shown in Fig. 13b, wherein a graphical representation was used to visualize

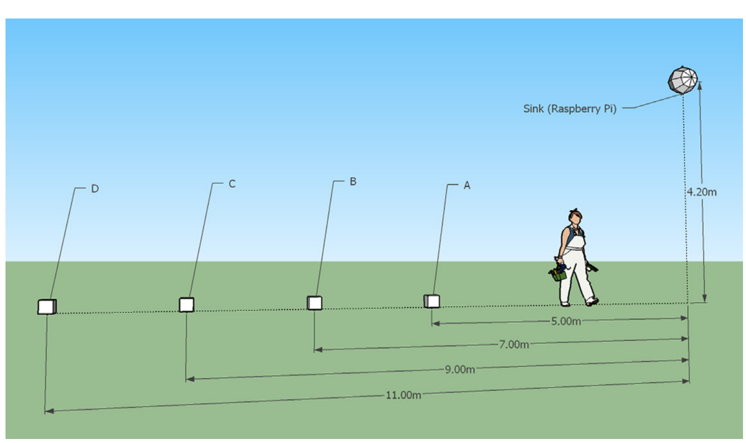


Fig. 10. Range test setup.

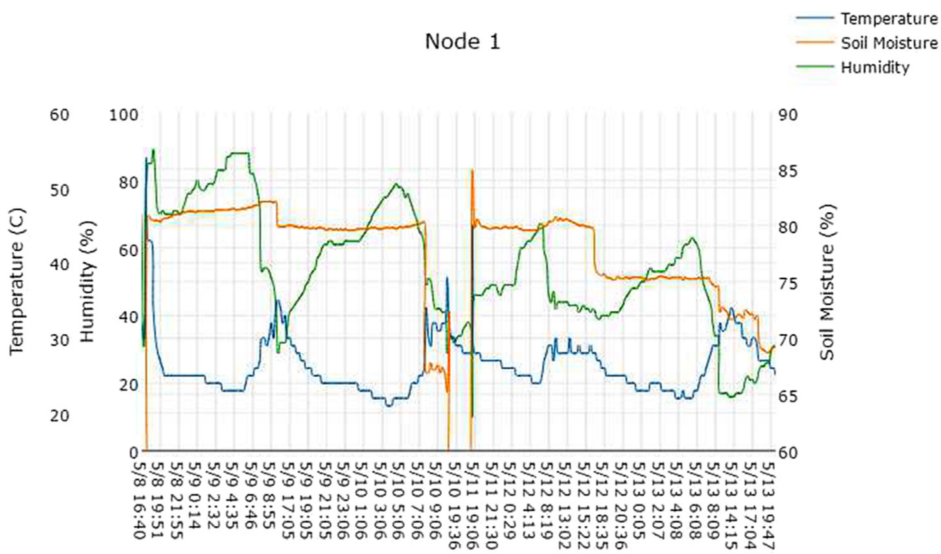


Fig. 11. Data in node 1 from field test.

Fig. 12. Actuation activity in node 5 from field test.

the 5-day activity of the sensor. Moreover, the water irrigation page shows the water volume consumed for each motor actuation executed by the system per day as deduced in Fig. 13c. The previous readings can also be viewed up to the last 30 days of monitoring available for all pages.

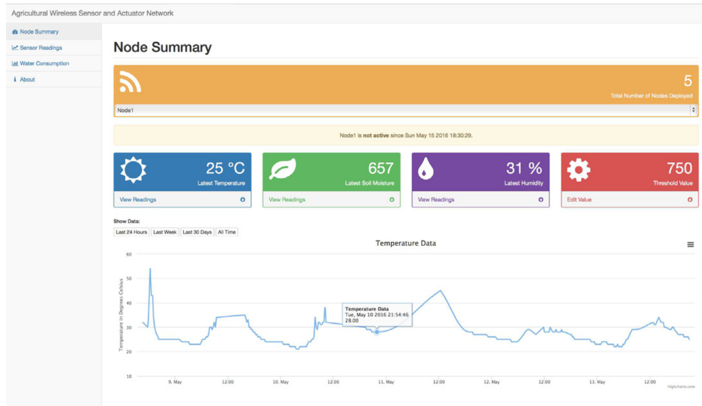
A survey about the user's experience in using the web application was conducted to gauge the responsiveness of the real-time graphs and node controls. The survey also take into account the device used in the overall appearance and experience. Generally, different users with various devices navigated the site with ease despite having different screen sizes.

Overall, the application's responsiveness and appearance gained favorable responses. A problem experienced by some users was the slow loading of graphs in the sensor reading page. This can be attributed to the device's network connection or the number of users simultaneously accessing the data as the application processes a considerable amount of data on the readings page.

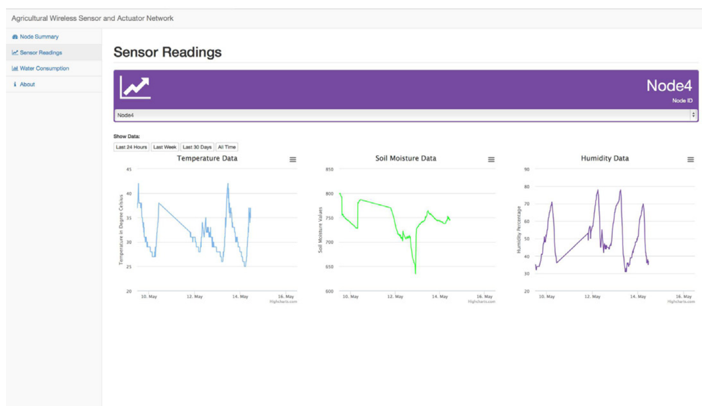
4. Conclusion and future directives

This work developed a mesh-based WSAN for water irrigation called Agrinex. The system is an alternative approach in collecting and measuring physical parameters from the environment particularly in smart irrigation systems. The mesh network is designed as dynamic and supports adding and subtracting of sensor nodes by allowing reorganizations. This makes Agrinex scalable and adaptable to changes in the network particularly in agricultural applications. The mesh-based network recorded a maximum transmission distance of 11 meters from sink to sensor node with 90% success rate. Data from the field can be accessed remotely close to real-time when short network delays are accounted for. It also gives the additional benefit of equipping the lands with an automated irrigation system that conserves up to 81% of water consumption.

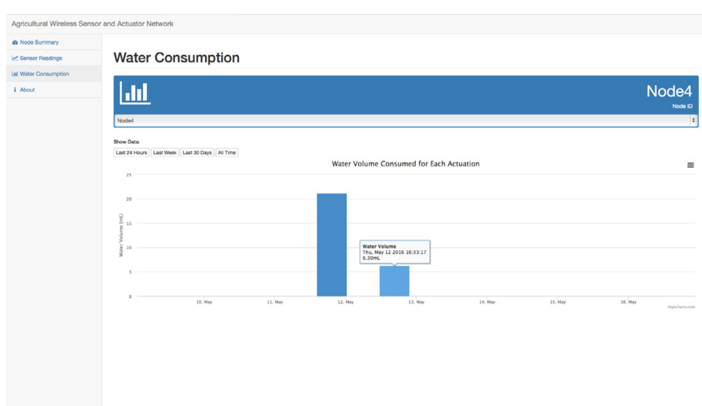
Agrinex is also cost-effective. The price of a single in-field node costs less than half the price of existing monitoring technologies in



(a) Node summary page



(b) Sensor reading page



(c) Water irrigation and actuation page

Fig. 13. Web-based application user interface.

the country and abroad. Installing the whole system is easy and will not be labor-intensive yet results and the overall benefits are extensive. The whole system's application is not limited in the agricultural sector. Any kind of sensor can be integrated in the developed hardware and software as long as it has the necessary pin outs: analog output for sensor value, VDD and GND. The actuator used in Agrinex requires 5 V input for actuation. Any similar actuator or motor can be easily integrated. Otherwise, the hardware can be easily modified to accommodate required voltage. Indeed, Agrinex is a promising initial framework for future Wireless Sensor and Actuator Networks endeavors not only in the agricultural field but in other applications as well.

In the future, it is recommended firstly, to enhance the transmission range and decrease delays of the system by opting to either use the enhanced nRF24L01 module that does not use an on chip antenna or use another transceiver altogether. Secondly, to test Agrinex system in a real agricultural land with a greater number of in-field nodes. Thirdly, to develop a reliable and long lasting power source for the in-field nodes and modify the web application to display the power status of the nodes. Fourthly, to modify the web application to allow user to program intervals of data acquisition and other periodic data transmissions. Moreover, it is suggested to use a real time clock to synchronize nodes and get more accurate time information. Finally, to develop the node to go to idle or sleeping state for better power performance.

Declaration of Competing Interest

None.

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