Implementing a Wireless Sensor Network with Multiple Arduino-Based Farming Multi-Sensor Tool to Monitor a Small Farm Area Using ESP32 Microcontroller Board

Aulivier Gilchrist Q. Aquino
School of EECE
Mapúa University
Manila, Philippines
agqaquino@mymail.mapua.edu.ph

Ballado, Alejandro H., Jr
School of EECE
Mapúa University
Manila, Philippines
ahballado@mapua.edu.ph

Azriell V. Bautista
School of EECE
Mapúa University
Manila, Philippines
avbautista@mymail.mapua.edu.ph

2021 IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM) | 978-1-6654-0167-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/HNICEM54116.2021.9731989

Abstract*—The Philippines is an agricultural country and in today's commercial agriculture, technology plays an important role in the development of different sectors of farm management, especially in resource utilization. This paper focuses on implementing a deployable wireless sensor network with multiple nodes centered in an ESP32 microcontroller board, wherein each sensor node has its own multiple sensors, using the ESP-WIFI-MESH protocol, which arranges the sensor nodes in a scalable, self-forming, self-healing, and autonomous mesh network topology for small farm-area monitoring. The input needed for this research are the plant growth parameters which include soil moisture, temperature, relative humidity, and ambient sunlight intensity; they will be obtained by the various sensors connected to a sensor node. The output is a collection of historical data to be displayed to and analyzed by farmers or other relevant groups. A node separation distance tested up to 100 meters can be achieved with RSSI of -88 dB. The paper also includes calibrations and testing to improve the capabilities of each node for 10 trials each, wherein the soil moisture has an RMSE=2.55% and SD=1.30%, the ambient sunlight intensity has RMSE=4.12 lux and SD=4.84 lux, the temperature has RMSE=1.31 °C and SD=0.50 °C, and lastly, for the relative humidity have an RMSE=1.73% and SD=0.96%. The power consumption of each of the nodes in the system is 0.865 W, wherein an average current draw of 173mA drawn from a power supply with a rated capacity of 10,000 mAh. The sensor nodes can last for up to 57.3 hours, but the power supply is charged during daytime with the help of solar panels.

Keywords*—*wireless sensor networks, farming, ESP32 microcontroller, ESP-WIFI-MESH

I. Introduction

The Philippines is considered an agricultural country, with 13.48 million hectares of land used for agricultural crop cultivation as of 2018 [1] which is 45.21% of the total area of land of the country that is 29.817 million hectares [2]. There is at least 67 billion cubic meters of agricultural water withdrawal every four years interval - that is 16.75 billion cubic meters of water per year [3]. Water is a valuable natural resource, and saving water in the agriculture sector through efficient irrigation is one way to reduce water consumption. Since most of the farms in the Philippines are still farming in traditional methods, resources like water are mostly used inefficiently in the process. As a solution to the limitations of traditional farming, smart farming is the modern alternative that addresses the limitations of traditional farming methods, which is efficiency without sacrificing production quality. With the integration of technology, data collection provides the farmers information for better management and decision-making support systems.

The study aims to implement a wireless sensor network with multiple Arduino-based farming multi-sensor tools to monitor a small farm area using an ESP32 microcontroller Board. The general objective of this study is to build a sensor network having individual "nodes" that can monitor multiple farming parameters. The purpose of designing the device with multiple nodes is that it can cover a wider range, thus providing a sort of information table to the farmers. Each "node" has its own multiple sensors, and these "nodes" record the values by sending it back to the "base station" by communicating wirelessly. Specifically, the study aims to achieve the following objectives: (1) fabricate four sets of farming multi-sensor devices based around the open-source Arduino-compatible ESP32 microcontroller development board that can primarily measure plant growth factors such as soil moisture, relative air humidity and temperature, and ambient sunlight intensity, (2) to make the four sets of farming multi-sensor device function as sensor nodes in a network (ESP-WIFI-MESH communication network) arranged in a mesh topology so as to make a simple information table of a farm area and check connectivity of nodes using RSSI, (3) to perform calibration on the sensor nodes and evaluate the proposed wireless sensor network, and lastly (4) to use statistical treatment to determine the efficiency of the sensor network in terms of accuracy, precision, and power consumption. The plant growth factors to be measured will be useful in farming situations where proper monitoring of the stated plant growth factors is needed.

II. Wireless Sensor Networks in Agriculture

In the field of agriculture, an inevitable role is played by wireless sensor networks, and the architecture is made up of a number of wireless sensor nodes which are used to collect and monitor data like soil moisture, carbon dioxide gas levels, humidity, and temperature [4]. With the use of cloud computing technology or the Internet, the data sensed and collected is transmitted to the human expertise, and the researchers in the central station can do analysis on the data and take further steps in order to increase the crop yield without high cost [4]. Comparing and contrasting smart farming with precision agriculture, there are some similarities and differences, such that smart farming focuses to get and monitor the farmland environment, while precision agriculture focuses to analyze data and information in order to support stakeholders and farmers in decision-making [5]. As elaborated in [5], precision agriculture is a concept regarding farming management that is based on the observation, measurement, and response to inter-field and intra-field variability in crops that can help the farmers to cut the costs as well as get the maximum yields and profits, by constructing a decision support system or DSS that is for the management of the entire farm and can optimize returns on inputs while conserving resources, and smart farming technologies, combined with data-driven precision agriculture.

Many research employs wireless sensor network in agriculture. A wireless sensor network that was developed monitors light, temperature, and humidity for monitoring in an agricultural environment of lettuce [6]. A greenhouse monitoring system using ESP8266 was designed such that it is cost-effective and highly reliable [7]. An environmental monitoring system was proposed in which an addition of an external 3 dBi antenna to an ESP32 was shown to allow communication up to 200 m [8].

In distributed formation techniques, a mesh logical topology and the information is managed by each node and decision making is resolved locally and is limited to its neighbors [9]. The main characteristics of this distributed network are its use of autonomous devices, the sharing of information of each node to its neighborhood, the information mainly being forwarded to a single node, lack of need for interconnection devices such as router and bridges, and flexibility that allows targeting harsh environments [9]. ESP-WIFI-MESH is a wireless communication protocol that connects nodes to form a scalable (up to 1000 nodes), self-forming and self-healing network with a mesh topology that operates on the WiFi frequency of 2.4 GHz as stated in the 802.11 standard [10].

III. METHODOLOGY

A. Conceptual Framework

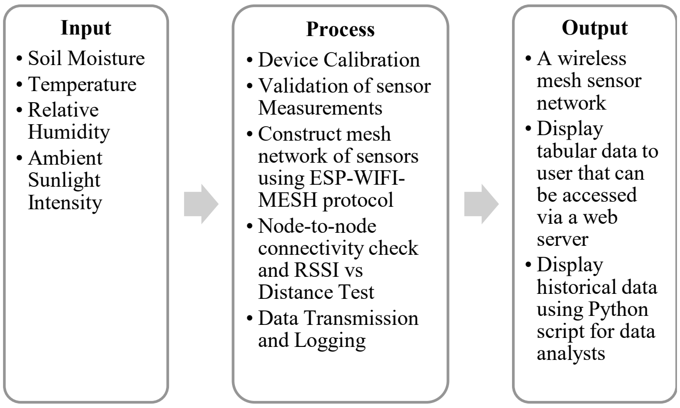

Fig. 1. Conceptual Framework

The conceptual framework for this research is shown above which is an input-process-output chart. The input needed for this research are the plant parameters which include soil moisture, temperature, humidity, and ambient sunlight intensity; they will be obtained by the various sensors connected to a sensor node, which will be in raw form as sensed by the microcontroller. For the process, the obtained raw plant parameters from the input will undergo calibration through curve-fitting to match their respective reference sensors known to have accurate measurements and then get validated. RSSI will also be tested to determine node placement. Also, with the layout being a wireless sensor network, each of the individual nodes will be constructed into a mesh topology which can achieved using the ESP-WIFI-MESH protocol of ESP32 microcontroller [11]. The data from each sensor nodes will be transmitted throughout the network and then gets logged once it reaches base station node. And lastly, the output is the wireless mesh network of sensor nodes created from the previously mentioned protocol that can monitor relevant farming parameters. The data will also be displayed similarly on a map form, which can then be accessed via a web server by connecting to a base station node. It can help the researchers and farmers alike in analyzing specific areas of the farm that lack in terms of the stated plant parameters. A Python script to plot the historical data from the logged data is also provided.

B. Research Process

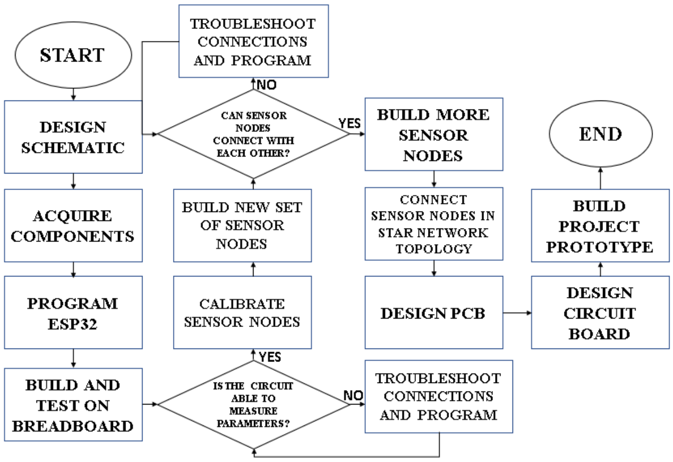

Fig. 2. Diagram of Research Process

This diagram depicts the steps to be taken in achieving the first three objectives. The sensor node schematic diagram is first designed depicting all the circuit components to be used. After acquiring the needed components, a program can be developed to be uploaded in the ESP32 microcontroller. After which is breadboard testing. If the sensor is not able to measure parameters, troubleshooting is done, and otherwise, if the sensor is able to measure the parameters, calibration can be done next. After which, another set of sensor nodes can be built. The connection between the two sensor nodes is checked. If they fail to connect, troubleshooting is done. Once the connection is successful, the other two sensor nodes can be built. The four sensor nodes will then be connected in a mesh network topology to form a wireless sensor network (ESP-WIFI-MESH). After which, the components will be soldered on a universal circuit board. Lastly, the prototypes of the sensor nodes will be built that can be placed on the soil.

C. Proposed Schematic Diagram

In the proposed mesh network, nodes are any device connected to it, in which we categorized it into two: a sensor node and a base station node.

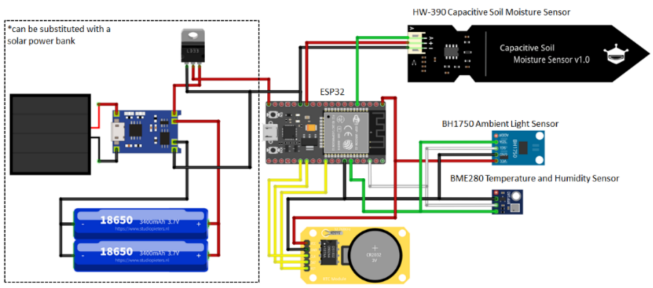

Fig. 3. Schematic of the Sensor Node

A sensor node is a node that has connected multiple sensors that gather the relevant farming parameters and is also responsible on relaying data on neighboring nodes until it reaches the base station node. For the measurement of the plant parameters, several sensor modules will be utilized (HW-390 for soil moisture, BH1750 for ambient sunlight intensity, and BME280 for temperature and relative humidity), as well as a real-time clock (RTC) module to get the date and time the measurement is taken. A high-capacity power source with a solar panel is to be used to power the sensor node.

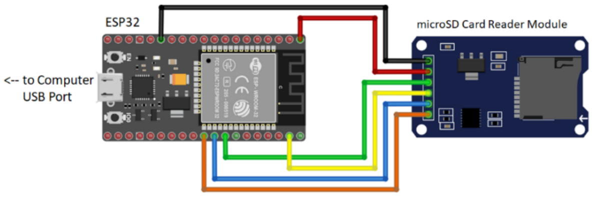

Fig. 4. Schematic of the Base Station Node

On the other hand, a base station node is a special node that is programmed to be responsible in the collection of data, as well as displaying it to the user via a webserver. The SD card will only be added to the base station node, but not in the sensor nodes. A secure digital (SD) card is used to store data locally when user is not connected to the base station node's web server. The base station needs to have a continuous source of power in order to operate (receive and store data). Although the base station only needs power and SD card to record data, connecting the base station to a USB serial port of a computer can help in analyzing the status of the network.

D. Overall System

Figure 5 shows the overall system of the proposed wireless sensor network in this paper, showing how the sensor nodes sense and send data to the base station node, to which the user can access and retrieve data through a web server. This system will be the one to be deployed as described in the paper.

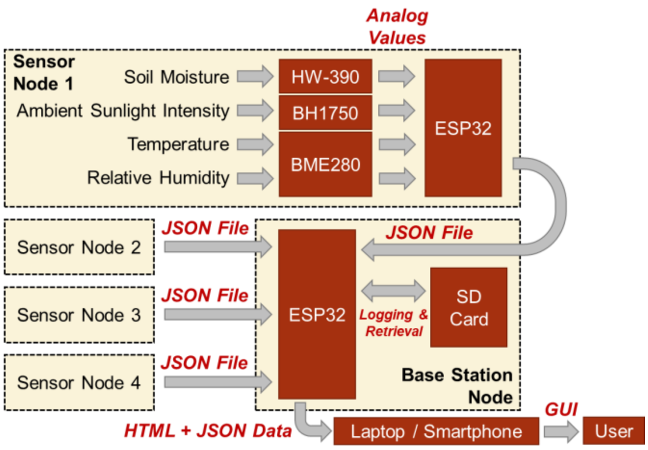

Fig. 5. Overall System

E. Calibration

1) *Curve Fitting by Quadratic Equation* – A polynomial equation of the second degree, i.e., a quadratic equation is to be created in the following form:

$$f(x) = a + bx + c^2 \qquad (1)$$

Wherein the values of coefficients a, b, and c will be found such that it best fits the data [12]. Reference sensors for soil moisture, light intensity, temperature, and relative humidity is to be used to get data to which the output of the built device will be fitted to. Curve fitting was done using an online application.

a) Calibration of Ambient Sunlight Sensor – For the process of calibration for the ambient sunlight intensity, the BH1750 ambient light sensor and the reference sensor are placed side by side and both their sensing elements positioned towards the sky, perpendicular to the ground. Then throughout the day, both their outputs were recorded to see their response on the varying sky light intensities. The output of the BH1750 were then calibrated to match the response of the reference sensor.

b) Calibration of Temperature and Humidity Sensor – For the calibration of the temperature and the humidity measurements, both the BME-280 and the reference sensor were placed in an a sealed container. A hot water was placed inside and measurements from both sensors were recorded until the water has reached normal room temperature. The same is done with the other spectrum of cold temperature to room temperature. The BME-280 sensor was calibrated to reflect the response of the reference sensor for both the temperature and humidity measurements. the tested range of temperatures were only of that can be typically found in an actual farm area.

2) *Calibration of Soil Moisture* – Soil samples of different types (sand, loam, clay, silt) were dried thoroughly, and water of increasing volume (25%, 50%, 75% and 100%) were added slowly in the dried soil samples. The soil moisture content were recorded for each of the soil samples with increasing soil moisture content, The HW-390 capacitive soil moisture sensor were calibrated in accordance with the reference sensor; a specific range was taken and mapped them to a percentage range that reflects the values from the reference sensor and generalizes all of the tested soil types as much as possible.

Fig. 6. Soil Moisture Sensor Calibration

3) *Reference Sensors* - For calibration and validation of the sensor measurements, reference sensors that can accurately measure the parameters were used. For soil moisture and sunlight intensity, the 3-in-1 Soil Meter was used as a reference device. For temperature and relative

humidity, a Digital Thermometer and Hygrometer was used as a reference device.

F. Wireless Sensor Network Topology

An ESP-WIFI-MESH wireless communication networking protocol will be used to create and organize the sensor nodes for longer range, which implements a mesh network topology that is easy to secure and setup, scalable up to 1000 nodes, self-arranging and self-healing (rearranges itself if a node is removed or disconnected). As stated in the objectives of this research, only four sensor nodes will be built, but this can be easily scaled up as the area to be monitored increases. Since the network is scalable, the user only needs to construct another set of a sensor node and change the NodeID variable in the source code to identify a new node. All of the sensor nodes are separated by some distance, and they are connected wirelessly via WiFi connection in a mesh topology using the aforementioned protocol [11]. The protocol creates its own network and does not rely on the Internet for its operation.

G. Base Station Web Server

A user has two options for data retrieval from the base station: (1) retrieve data directly by taking out the SD card from the base station node and using an SD card reader to get the file, or (2) connect to the Wi-Fi access point and access the web server using a computer or smartphone and download the data there as a JSON file. The created webserver can detect the unique nodes that was present in the data logs from the SD card in the base station node, and it will display this at the topmost portion of the web server. An interface will then be visible for the user to interact with, which displays the latest reading from a particular node, filter the data by node, and plot the data of each parameter for the nodes present.

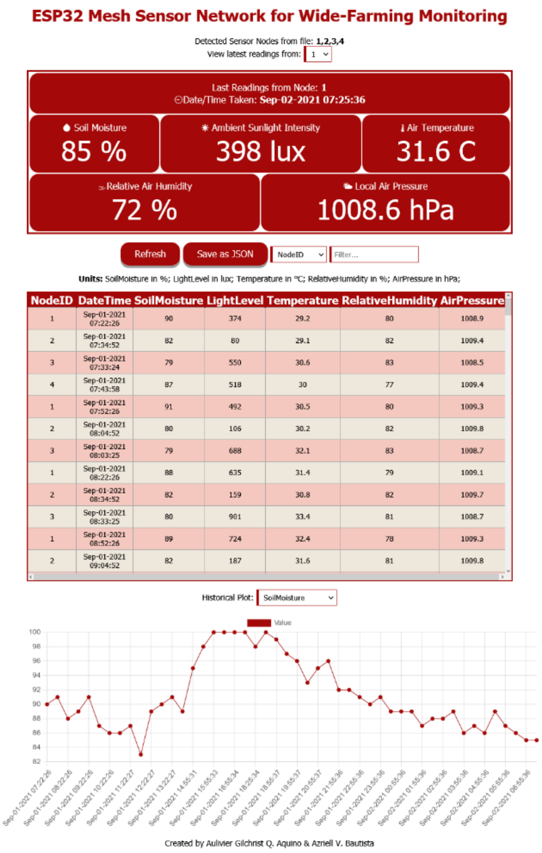

Fig. 7. Web Application GUI in Base Station

H. Nodes Set-up

Fig. 8. Picture of Sensor Node Set-up

Figure 8 illustrates the set-up for each sensor node. The enclosure for a sensor node is made of plastic material which houses the ESP32 microcontroller, and other circuitries. A small hole allows the BME280 sensor to detect temperature and relative humidity in the air. A long hollow but sturdy pole supports the whole enclosure as well as to provide a line of sight to other neighboring nodes. At the end of the pole, a capacitive sensor is fixed to measure the soil moisture. A wire runs through the pole to reach the ESP32 microcontroller. A solar power bank is placed on top of the enclosure which charges the batteries during daytime. The light sensor was placed just beside the solar panel, pointing straight to the sky.

I. Test Set-up

For the test set-up, the four sensor nodes were placed on four areas with distinct soil characteristics and ambient sunlight intensity. Sensor nodes 1, 2, 3, and 4, were placed on a pot with clay, loam, sand, and silt, respectively.

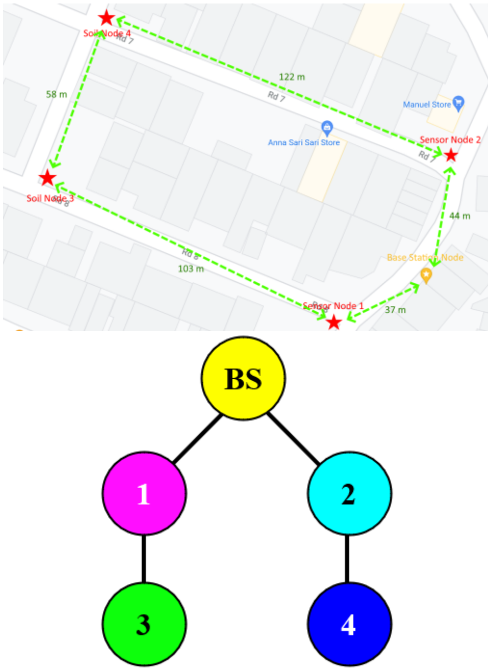

Fig. 9. Node Placement and Network Connectivity

J. Testing of the Wireless Sensor Network

The accuracy and precision of measurements was determined with root mean square error (RMSE), and standard deviation (SD), as well as the power consumption of the sensor nodes. A 24-hour test was done to measure the parameters in 30 minutes interval and graphed with a Python script.

IV. Results and Discussion

A. Plant Growth Parameters

1) RMSE and SD per Parameter – For ten trials, the parameters were measured and the accuracy (RSME) and precision (SD) of the sensor measurements is indicated in the table below. It shows that the sensor measurements are accurate and precise.

TABLE I. RMSE and SD Values for Each Plant Growth Parameter

	Parameters			
	Soil Moisture	***Ambient Sunlight Intensity***	***Temperature***	***Relative Humidity***
RMSE	2.55%	4.12 lux	1.31 °C	1.73%
SD	1.30%	4.84 lux	0.50 °C	0.96%

2) Soil Moisture – An increase in moisture content of the soil seen around 4:00pm is caused by a rainfall and are maintained differently by the varying soil types, from which the water retention can be concluded as in the table.

TABLE II. Water Retention for Different Soil Types

	Node 1 (Clay)	**Node 2 (Loam)**	**Node 3 (Sand)**	**Node 4 (Silt)**
Water Retention	High	Medium	Medium	Low

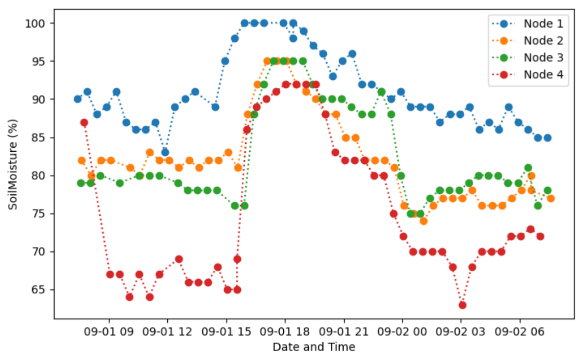

Fig. 10. Soil Moisture Measurements

3) Ambient Sunlight Intensity – The variation in ambient sunlight from each node is caused by the placements of the nodes, in which there may be shades produced by a tree or a wall. The ambient sunlight level is peak at noon, and no sunlight at night. The sunlight decreased midday due to rain.

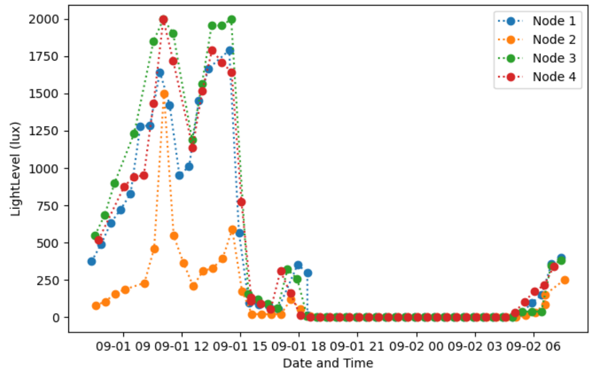

Fig. 11. Ambient Sunlight Intensity Measurements

4) Temperature – The temperature peaked at noon. It was generally hotter at day and cooler at night. The drop in temperature midday was due to the rain.

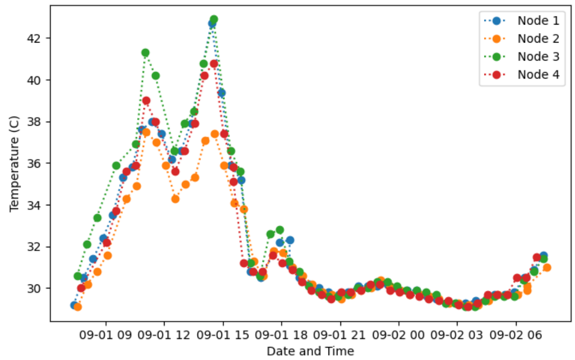

Fig. 12. Temperature Measurements

5) Relative Humidity – The rise in humidity at 4:00 pm was due to rain. A rise in humidity can be used to predict imminent rain. Generally, the relative humidity is decreasing at daytime and increasing at nighttime.

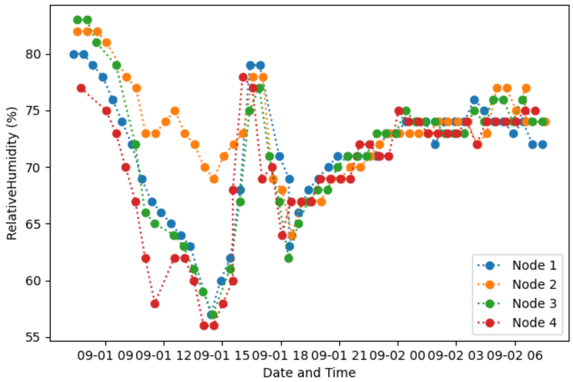

Fig. 13. Relative Humidity Measurements

B. Power Consumption

From the power consumption test, the testing meter showed that the average current draw for the continuous operation of the sensor node for an hour is 173 mA. Using the specified capacity of the solar power bank integrated in the sensor node, which is 10,000 mAh, it can be computed that a sensor node can ideally last 57.3 hours, not taking into consideration that the power bank charges through sunlight during daytime for the following days. The power consumption of the system is 0.865 W, which is higher than the system mentioned in [13] which has 0.01 W or 42.17 J/h.

C. Connectivity Check

1) RSSI for Node Pairs – The following verifies the network connectivity of the nodes.

TABLE III. RSSI Values for Node Pairs

From / To	**SN1**	**SN2**	**SN3**	**SN4**	**BSN**
SN1	--	--	-90 dB	--	-84 dB
SN2	--	--	--	-96 dB	-86 dB
SN3	-90 dB	--	--	-90 dB	--
SN4	--	-96 dB	-90 dB	--	--
BSN	-84 dB	-86 dB	--	--	--

2) RSSI vs Distance between Two Nodes Check – It is shown below that, with the on-board antenna of ESP32, an acceptable RSSI of -88 dB is achieved up to a distance of 100 meters.

TABLE IV. RSSI VS DISTANCE BETWEEN TWO NODES

RSSI vs Distance Between Two Nodes	
Distance (m)	**RSSI (dB)**
1	-47
2	-54
5	-65
10	-70
20	-78
25	-81
100	-88

V. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

A wireless sensor network was successfully developed and tested for farm monitoring, specifically measuring plant growth factors such as soil moisture, ambient sunlight intensity, relative humidity, and temperature. With the use of ESP-WIFI-MESH protocol with the ESP32 microcontroller, it is possible to create a self-arranging and self-healing network with a distance of up to 100 m per two nodes, and also independent to the Internet. Application of this wireless sensor network includes smart farming for achieving better crop quality yield. More effective resources management is possible through monitoring of plant growth factors, so that resources can be utilized wisely.

B. Recommendations

It is recommended to test the proposed mesh network of sensor in an actual farm, an area where there is less obstruction between nodes. Use the presented nodes to automate processes such as irrigation. An external antenna can be added to the nodes to further increase their range, and even employing low power modes to increase battery longevity.

ACKNOWLEDGMENT

A. V. B. appreciates the Department of Science and Technology - Science Education Institute (DOST-SEI) for their unwavering support to their scholars.

REFERENCES

[1] "Philippines: land area used for agricultural crop cultivation." [Online]. Available: https://www.statista.com/statistics/1045556/land-area-used-for-agricultural-crop-cultivation-philippines/. [Accessed: 06-Sep-2020]

[2] "Land area (sq. km) - Philippines." [Online]. Available: https://data.worldbank.org/indicator/AG.LND.TOTL.K2?locations=PH. [Accessed: 05-Sep-2020]

[3] Food and Agriculture Organization of the United Nations (FAO), "AQUASTAT database." [Online]. Available: http://www.fao.org/nr/water/aquastat/data/query/results.html. [Accessed: 11-Sep-2020]

[4] T. Rajasekaran and S. Anandamurugan, "Challenges and Applications of Wireless Sensor Networks in Smart Farming—A Survey," *Advances in Intelligent Systems and Computing*. pp. 353–361, 2019 [Online]. Available: http://dx.doi.org/10.1007/978-981-13-1882-5_30

[5] S. Suakanto, V. J. L. Engel, M. Hutagalung, and D. Angela, "Sensor networks data acquisition and task management for decision support of smart farming," *2016 International Conference on Information Technology Systems and Innovation (ICITSI)*. 2016 [Online]. Available: http://dx.doi.org/10.1109/icitsi.2016.7858233

[6] C. N. Cabaccan, F. R. G. Cruz, and I. C. Agulto, "Wireless sensor network for agricultural environment using raspberry pi based sensor nodes," in *2017IEEE 9th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)*, Manila, 2017, doi: 10.1109/hnicem.2017.8269427 [Online]. Available: http://dx.doi.org/10.1109/hnicem.2017.8269427

[7] T. Cao Pham, H. Bich Vo, and N. Quang Tran, "A Design of Greenhouse Monitoring System Based on Low-Cost Mesh Wi-Fi Wireless Sensor Network: *Note: Sub-titles are not captured in Xplore and should not be used," in *2021 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS)*, Toronto, ON, Canada, 2021, doi: 10.1109/iemtronics52119.2021.9422655 [Online]. Available: http://dx.doi.org/10.1109/iemtronics52119.2021.9422655

[8] M. Catelani, L. Ciani, A. Bartolini, G. Guidi, and G. Patrizi, "Characterization of a low-cost and low-power environmental monitoring system," in *2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Dubrovnik, Croatia, 2020, doi: 10.1109/i2mtc43012.2020.9129274 [Online]. Available: http://dx.doi.org/10.1109/i2mtc43012.2020.9129274

[9] M. Carlos-Mancilla, E. López-Mellado, and M. Siller, "Wireless Sensor Networks Formation: Approaches and Techniques," *Journal of Sensors*, vol. 2016, Mar. 2016, doi: 10.1155/2016/2081902. [Online]. Available: https://www.hindawi.com/journals/js/2016/2081902/. [Accessed: 10-Oct-2020]

[10] ESPRESSIF SYSTEMS, "ESP-WIFI-MESH," *ESPRESSIF*. [Online]. Available: https://www.espressif.com/en/products/sdks/esp-wifi-mesh/overview. [Accessed: 31-Aug-2021]

[11] "ESP-WIFI-MESH - ESP32 - — ESP-IDF Programming Guide latest documentation." [Online]. Available: https://docs.espressif.com/projects/esp-idf/en/latest/esp32/api-guides/esp-wifi-mesh.html. [Accessed: 02-Sep-2021]

[12] S. Attaway, "Advanced Mathematics," in *Matlab*, Elsevier, 2017, pp. 503–556 [Online]. Available: https://www.sciencedirect.com/topics/engineering/quadratic-curve. [Accessed: 29-Aug-2021]

[13] H. M. Jawad, R. Nordin, S. K. Gharghan, A. M. Jawad, and M. Ismail, "Energy-Efficient Wireless Sensor Networks for Precision Agriculture: A Review," *Sensors* , vol. 17, no. 8, Aug. 2017, doi: 10.3390/s17081781. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5579920/. [Accessed: 09-Oct-2020]