Wireless sensor network using nRF24L01+ for precision agriculture

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ABSTRACT

Precision agriculture is a strategy for varying inputs and cultivation methods to suit varying soil conditions and agricultural crops. In order to optimize precision agriculture, wireless sensor network (WSN) is suitable to be integrated. In this research, network devices that communicate using nRF24L01+ based WSN was proposed. As a prototype, four sensor nodes were employed to measure the parameters of air temperature and humidity, soil moisture, and power supply voltage. While, a sink node serves to store measurement data locally. The data are sent to the sink node with a mesh network topology and saved in a comma-separated values (CSV) file and local database. Experimental results show that each sensor node can measure all parameters and successfully send data to the sink node every 1 minute without losing the data. The mesh topology can route data transfer automatically. Round trip time (RTT) of each sensor node depends on the distance from each node. Average power consumption of all sensor nodes in send mode is between 84 mW and 90 mW. Meanwhile, in sleep mode, the sensor nodes 1 and 2 consumed around 21-22 mW and the sensor nodes 3 and 4 consumed around 30 mW which are lower than the send mode.

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1. INTRODUCTION

Precision farming is a smart concept that allows farmers to manage the spatial and temporal variability of agricultural crops. In the realm of modern agriculture, the integration of technology has become indispensable for optimizing crop yields, resource utilization, and environmental sustainability [1], [2]. One of the pivotal advancements in this domain is the application of wireless sensor network (WSN) to monitor and manage agricultural fields with a high degree of precision [3]-[12].

WSN has gained prominence in precision agriculture due to its ability to gather real-time data from distributed sensors deployed across fields. This network provides a means to monitor and control various parameters including soil moisture, temperature, humidity, light intensity, and even nutrient levels. Data from the parameters can be invaluable for making informed decisions related to irrigation scheduling, fertilization, pest control, and crop health assessment [13]-[17]. A WSN consists of a group of specialized autonomous sensors and actuators with wireless communication infrastructure to transmit the desired data or control commands. Network devices in WSN that sense, collect, and measure various information from the surrounding environment where it is deployed and can send that data to WSN system users are called as sensor nodes. Another network device is a sink node [1], [18]. Most WSNs are built using internet connections. There are several network topologies available for the WSN. Previous study in [19] evaluated internet based WSN using three topologies, i.e., star, tree, and mesh topologies. The WSN and internet of things were widely used together with several platforms for various applications [20]-[24]. However, in some cases, agricultural fields are not covered by internet connection. Internet free-based communication is needed to build the WSN in this situation.

Radio frequency (RF) module such as nRF24L01+ wireless transceiver module has emerged as a key enabler for such networks, offering low-power communication, cost-effectiveness, and reliable data transmission in the challenging outdoor agricultural environments. The nRF24L01+ wireless transceiver module stands out as an essential component in WSNs for precision agriculture. Developed by Nordic Semiconductor, the nRF24L01+ offers a balanced blend of characteristics that are well-suited for the demands of agricultural applications. Its low power consumption facilitates extended operational lifetimes, a crucial factor for remote deployments where access to power sources may be limited. Additionally, the nRF24L01+ boasts a moderate communication range and data rate, fitting the requirements of field-scale operations [25]-[27]. Detail specifications of the nRF24L01+ are presented in Table 1.

In this research, we delve into the convergence of WSNs and precision agriculture through the lens of internet-free module, i.e., nRF24L01+ transceiver module. We explore the technical aspects of deploying such networks, including hardware considerations, communication protocols, data management, and power management. Furthermore, the nRF24L01+-based WSN is also examined and compared based on two network topologies.

Table 1. Specifications of nRF24L01+

No	Parameters	Value
1	Frequency range	2.4 GHz ISM band
2	Maximum air data rate	2 Mbps
3	Modulation format	GFSK
4	Max. output power	0 dBm
5	Operating supply voltage	1.9 V to 3.6 V
6	Max. operating current	13.5 mA
7	Min. current (standby mode)	26 μA
8	Logic inputs	5 V tolerant
9	Communication range	800+ m (line of sight)

2. METHOD

2.1. Wireless sensor network general overview

The WSN is illustrated in Figure 1. There are several blocks that interact with each other to form the working system of the WSN. Node 0 serves as the sink node and server. This node receives all the reading data from the sensor nodes, which is then stored locally. Meanwhile, nodes 1-4 act as sensor nodes responsible for sensing some precision agriculture parameters. The data from the sensing process is then transmitted to the sink node.

Based on the designed WSN system block diagram, the working principle is as follows. Each sensor node reads temperature, air humidity, and soil moisture around the nodes. Furthermore, each sensor node also reads voltage values from the power supply at intervals of every few minutes. The sensor reading data is then sent to the sink node. After successfully transmitting the data to the sink node, the sensor node goes into a sleep mode until it's time to read and send data again or until it receives data from other sensor nodes. The sink node receives and collects data from other nodes, storing it locally in comma-separated values (CSV) files and also in a database. Therefore, the sink node remains active 24 hours a day to ensure the WSN works properly without losing data.

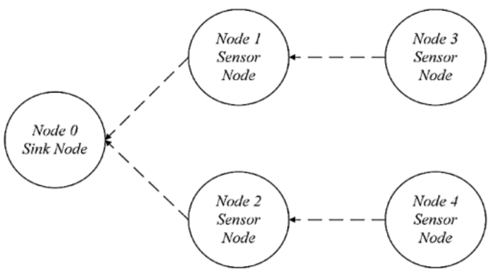
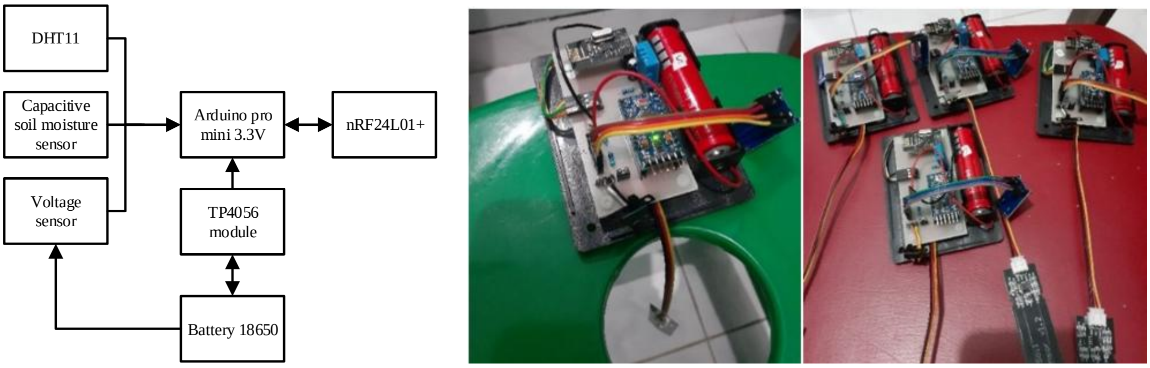


Figure 1. WSN illustration

2.2. Hardware design

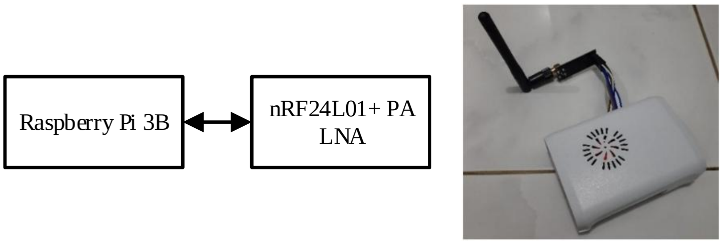
WSN supporting hardware is divided into two parts, namely hardware of sensor node and sink node. The sensor nodes were built based on block diagram in Figure 2(a) which its realization is shown in Figure 2(b). Each sensor node consists of Arduino Pro Mini as subsystem of computing and nRF24L01+ as subsystem of communication. These nodes are also supported by subsystem of power supply consists of TP4056 module as charger and protector of rechargeable lithium battery (18650). Another one is subsystem of sensing which consists of DHT11 which is digital temperature and capacitive humidity sensor, capacitive soil moisture sensor, and voltage sensor.



(a) (b)

Figure 2. Sensor nodes in: (a) block diagram and (b) realization

The sink node was built based on block diagram in Figure 3(a) which its realization is shown in Figure 3(b). The sink node is assigned to receive all sensing data and store it locally. Therefore, Raspberry Pi 3B is used as computing subsystem of the sink node. Furthermore, nRF24L01+ PA LNA was attached to realize its communication subsystem.



(a) (b)

Figure 3. Sink node in: (a) block diagram and (b) realization

2.3. Software design

The sensor nodes of the WSN run following flowchart as shown in Figure 4. When the node is first turned on, the node will create a network on a certain radio channel and configure the node address on the network that has been created. The Arduino Pro Mini will start reading sensor data. The data will be temporarily stored before sending. The node sends the data to the sink node. When the delivery is hampered by problems, the auto retry feature will be activated and the delivery will be carried out again with the specified pause and repetition values. After the sending is done, the microcontroller starts the sleep mode. This function will put the node to sleep, with the radio still active in standby-1 mode. Standby-1 mode can wake up the node automatically if it receives a payload.

The sink node of the WSN has a flowchart shown in Figure 5. When it is first turned on, the sink node will create a network on a certain radio channel. As well as configuring the node addresses on the network that has been created. After the network is formed, the nodes are then in an idle state. If there is incoming data, the node will start the process of reading the payload data. Data that has been read will be stored temporarily until this data is processed or other data is entered. The data received will be converted and processed before finally being saved into a CSV file and uploaded to the database.

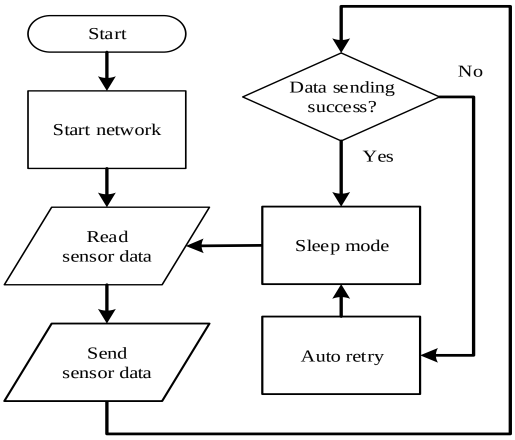


Figure 4. Flowchart of sensor nodes

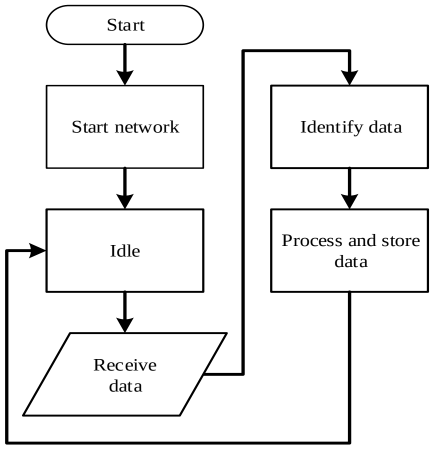


Figure 5. Flowchart of sink node

3. RESULTS AND DISCUSSION

Several experiments have been conducted to confirm the performance of the built WSN. In this section, some experiment results will be reported. Discussion will also be provided for each sub section.

3.1. Soil moisture sensor

Experiment of soil moisture sensor follows procedure as follows. The sensor measures moisture data from sample (soil). The sensor response in the form of voltage value was recorded. Moisture data from the sample was measured using a volumetric approach. The soil sample was dried by flattening in open air. Next, the sample is placed in four plastic containers. The samples experienced an increase in water volume of 0%, 10%, 20%, 40%, 60%, 80%, and 100% respectively. Percent volume addition is based on volume addition in ml compared to total soil volume. For example, adding 10 ml of water to 100 ml of soil means an increase in water volume of 10%. The experiment result is shown in Figure 6. It can be seen that the output voltage value of the soil moisture sensor becomes smaller as the water percentage in the soil increases. It means that the moister the soil, the smaller the output voltage of the sensor. So, the sensors can work properly.

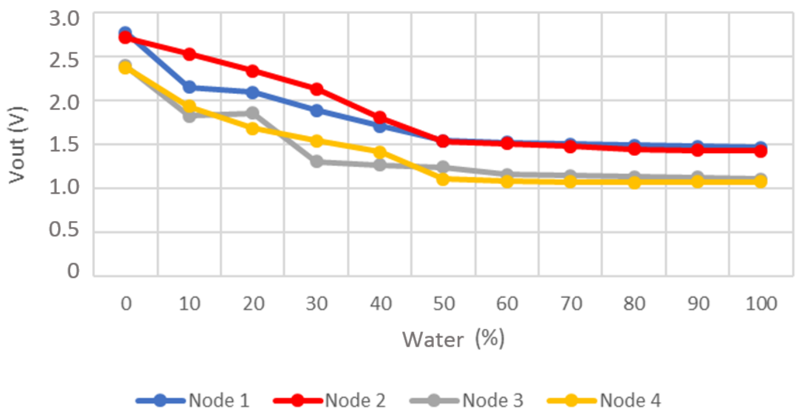


Figure 6. Experiment result of soil moisture sensor of sensor nodes

3.2. Temperature and humidity (DHT11)

Experiment of temperature and air humidity sensors was conducted by comparing the sensor output values with the output values read on other temperature and air humidity measuring instruments (considered to be true values). Error percentage was calculated using (1) [28]:

$$\%\ error = \frac{|Sensor\ value - True\ value|}{True\ value} \times 100\% \quad (1)$$

Table 2 shows that average error percentage of temperature values by sensor nodes 1, 2, 3, and 4 are 2.73%, 2.05%, 3.58%, and 2.48%, respectively. Table 2 also summarizes average error percentage of humidity values by sensor nodes 1, 2, 3, and 4 are 3.2%, 3.66%, 5.8%, and 4.89%, respectively. Most of them are less than 5%.

Table 2. Error of temperature values

No	Error of temperature values (%)				Error of humidity values (%)			
	Sn 1	Sn 2	Sn 3	Sn 4	Sn 1	Sn 2	Sn 3	Sn 4
1	2.57	1.84	2.21	1.47	0	1.32	3.95	2.63
2	2.42	1.52	1.21	3.03	6.45	0	1.61	11.29
3	1.78	0	0.71	0.36	7.04	7.04	8.45	8.45
4	1.44	0.72	1.81	2.53	8.22	4.11	6.85	1.37
5	0.72	0.36	1.09	2.17	0	1.35	5.41	0
6	5.75	4.47	6.71	7.67	0	1.61	4.84	6.45
7	2.58	1.61	5.81	2.58	1.67	6.67	5	3.33
8	5.1	3.82	5.73	0.96	1.72	3.45	6.9	8.62
9	2.19	4.08	6.9	1.57	3.7	7.41	9.26	1.85
Average	2.73	2.05	3.58	2.48	3.2	3.66	5.8	4.89

*SN: sensor node

3.3. Voltage

Experiments were carried out on four sensor nodes to analyze performance of the voltage sensors when reading battery voltage values. Voltage values of eight batteries were tested with a voltmeter. Then, each voltage sensor component in the form of a voltage divider circuit was connected to Arduino Pro Mini 3.3 V according to the sensor node design to form four sensor nodes. Each sensor node was connected to a laptop in order to test eight batteries. The sensor reading results were shown in serial monitor. Each battery underwent the same experiment for four sensor nodes. Evaluation was conducted by comparing the sensor output voltage values with the voltage value read on the voltmeter (considered to be true values). Calculating error percentage using (1), the results are summarized in Table 3. The sensors worked well with small error percentage.

Table 3. Error of voltage values

Battery	Error of voltage values (%)			
	Sensor node 1	Sensor node 2	Sensor node 3	Sensor node 4
1	0.22	0.24	0.13	0.42
2	0.02	0.50	0.24	0.17
3	0.07	0.28	0.02	0.38
4	0.21	0.26	0.12	0.52
5	0.03	0.39	0.39	0.27
6	0.21	0.40	0.47	0.15
7	0.03	0.39	0.27	0.25
8	0.17	0.28	0.23	0.35
Average	0.12	0.34	0.23	0.31

3.4. Network topology

Network topology testing was carried out to analyze the performance of the nRF24L01+ modules in creating data transfer routes based on network topology. There are two network topologies tested, namely tree and mesh topologies. This test focuses on the results of the addresses received by each sensor node and then the network route formed can be seen. This test also analyzes in more detail the creation of data transfer routes and also the process of sending data between nRF24L01+ modules in a mesh topology. The test data is 32 bytes in size, consisting of character (23 bytes), packet counter (1 byte), millis time (4 bytes), and node number (4 bytes).

Sink node and sensor nodes were arranged following the illustration shown in Figure 1. Experiment results in Table 4 show a comparison between mesh and tree topologies. When the tree topology is executed, the process of creating data routes is carried out manually by entering the network address according to the addressing standards of nRF24L01+ (see Table 5) into each existing node. Where the network address of nodes in a mesh topology is dynamic while the network address of nodes in a tree topology is static. Dynamic addresses in a mesh network topology mean that when an error occurs on a sensor node which causes the network route to be damaged, other sensor nodes can reconnect and create a new network route.

Table 4. Testing results of tree and mesh topologies

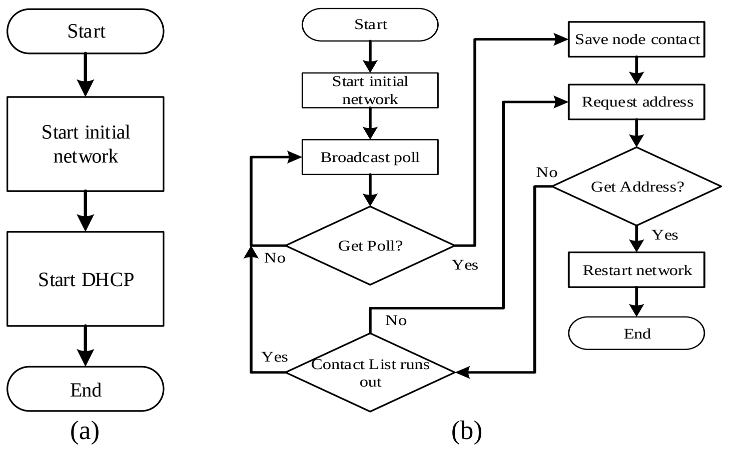
No	Conditions	Network address (tree topology)				Network address (mesh topology)			
		Node 1	Node 2	Node 3	Node 4	Node 1	Node 2	Node 3	Node 4
1	All sensor node on	05	04	045	044	05	04	045	044
2	Node 1 off	−	04	−	044	−	04	034	044
3	Node 1 on again	05	04	045	044	05	04	045	044
4	Node 2 off	05	−	045	−	05	−	045	0445
5	Node 2 on again	05	04	045	044	05	04	045	0445
6	Node 3 off	05	04	−	044	05	04	−	044
7	Node 3 on again	05	04	045	044	05	04	045	044
8	Node 4 off	05	04	045	−	05	04	045	−
9	Node 4 on again	05	04	045	044	05	04	045	044

Table 5. nRF24L01+ network addressing standard

Address level 0 (master node 00)	00									
Address level 1 (node 01 - 05)			01				05			
Address level 2 (node 0nn – 0nn)		011	...	051				015	...	...
Address level 3 (node 0nnn – 0nnn)	0111	...	0151	...	0551	...			0115	...
Address level 4 (node 0nnnn – 0nnnn)	01111	...	01151	...	01551	...		01115	02115	03115

*n value is 1-5

Meanwhile, the process of creating the nRF24L01+ mesh topology data route follows the flowchart shown in Figure 7. The sink node creates and starts the network, then activates a function like dynamic host configuration protocol (DHCP) to distribute network addresses to requesting nodes as illustrated in Figure 7(a). While Figure 7(b) shows flowchart of the sensor nodes in creating the route. The sensor node starts the network, then carries out a broadcast poll process to scan 4 other nodes in the surrounding area. Broadcast polls are carried out following the order of address levels from lowest to highest (level 0-3). This poll process is carried out repeatedly until a successful poll is obtained. After successfully obtaining poll data, the sensor node will store the data into a node contact array with the elements ordered based on signal strength from highest to lowest. Then, the sensor nodes send address request messages with the sink node as a target, which are sent to the first element contact node. If a sensor node is failed, it will send a message again to the next element in the contact node. When a sensor node is unable to obtain the address and the node's contact list has run out, the sensor node will carry out the broadcast poll process again. If the sensor node successfully obtains the address resulting from the DHCP sharing of the sink node, then it will restart and enter the network with the received address.



(a) (b)

Figure 7. Flowchart of creating mesh topology data route: (a) sink node and (b) sensor nodes

An example of the broadcast poll process for creating nRF24L01+ mesh network topology data routes is shown in Figures 8 and 9. Figure 8 shows the broadcast poll process from sensor nodes during initial network creation. Nodes 1 and 2 broadcast polls only at address level 0 because they immediately succeeded in finding the sink node. Then make an address request to the sink node (see Figure 9). Meanwhile, nodes 3 and 4 failed to broadcast poll at address level 0, because the distance was too far from the sink node. Then perform a broadcast poll at address level 1 and each node successfully finds a connecting node. Next, each node sends an address request message with the target message is the sink node. This message will be sent to the connecting node so that it can then be forwarded to the sink node.

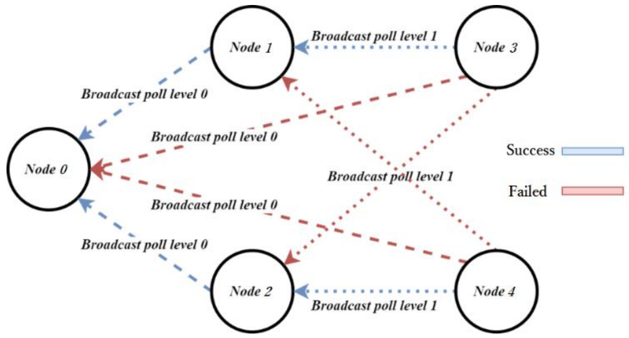


Figure 8. Broadcast poll process during initial network creation

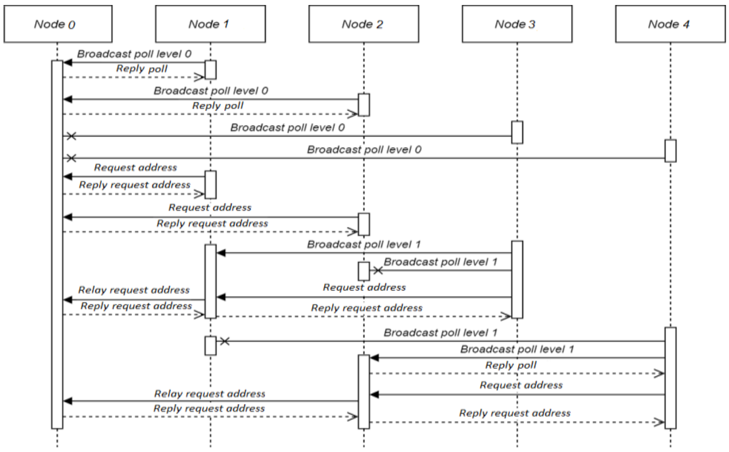


Figure 9. Address request process during initial network creation

There are 2 data transfer scenarios on the nRF24L01+ module. The data transfer process for scenario 1 is shown in Figure 10. Node 1 sends data to node 0, then waits for an acknowledgment (ACK) reply for a certain time. After receiving the data, node 0 will wait a few moments and then send an ACK reply to node 1. Finally, node 1 successfully receives the ACK reply. The data transfer process for scenario 2 is shown in Figure 11. Node 1 sends data to node 0, then waits for an ACK reply for a certain time. After receiving the data, node 0 will wait for the ACK sending time and then send an ACK reply to node 1. However, if the ACK sending is hampered by problems, for example node 1 does not receive an ACK reply until the specified time, then the data will be resent to node 0. After receiving the data, node 0 will wait for the time to send the ACK and then send an ACK reply to node 1. Finally, node 1 successfully receives the ACK reply.

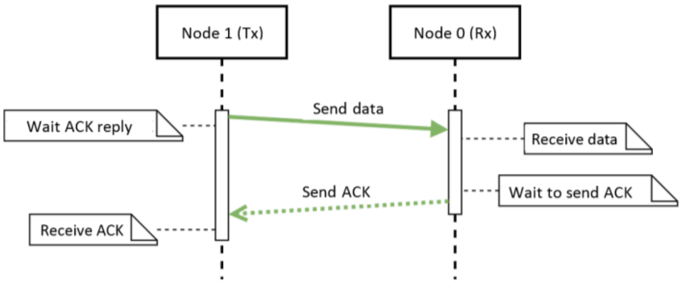


Figure 10. Data transfer using scenario 1

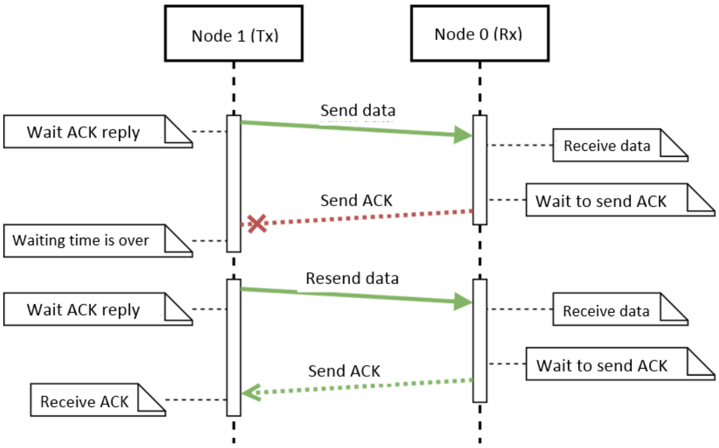


Figure 11. Data transfer using scenario 2

3.5. Round trip time

RTT testing is carried out by measuring the time required for one node to send data to another node until it receives a reply message or ACK from the destination node. In this test, the sink node served as the data receiving node, and 4 sensor nodes served as data senders. This test was carried out on both tree and mesh topologies with distance between nodes of around 1 meter. The same 32 byte data is used in 10 times sending data.

Average RTT (in ms) of the mesh topology by nodes 1, 2, 3, and 4 are 2.45, 2.45, 13.07, and 13.10, respectively. While average RRT (in ms) of the tree topology by nodes 1, 2, 3, and 4 are 2.40, 2.40, 13.02, and 12.98, respectively. Average RTT of nodes 1 and 2 are same and nodes 3 and 4 are nearly same. However, the 2 node pairs have different average RTT because the distance on node placement will have an effect on data transfer where the farther the sensor node is from the sink node, the RTT will also be greater, because the node must perform multi-hop when sending messages. Figure 12 indicates all nodes perform high stability in transferring data.

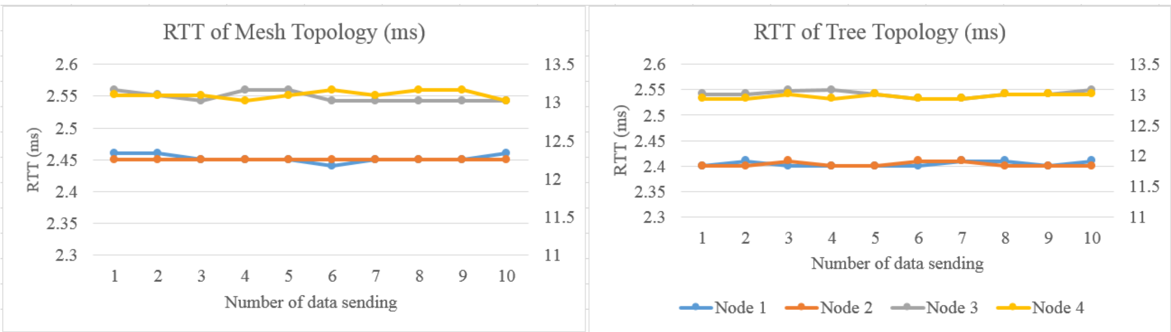


Figure 12. RTT experiment results

3.6. Wireless sensor network performance

WSN performance was confirmed by overall system experiment. All program run with the sensor nodes send data once a minute. The sensor node will activate sleep mode when not sending data. Mesh topology was used to conduct this experiment. The data is 22 bytes in size, consisting of node_id data (4 bytes), temperature (4 bytes), air humidity (4 bytes), soil moisture level (2 bytes), soil moisture voltage (4 bytes), and battery voltage (4 bytes). The experiment results show that the data sent from sensor nodes, i.e., node_id, air temperature and humidity, soil moisture level, soil moisture voltage, and battery voltage have been successfully received and processed by the sink node. The sink node has successfully saved node_id data, air temperature and humidity, soil moisture level, soil moisture voltage, and battery voltage into a CSV file (Figure 13) and uploaded to mySQL database (Figure 14). The figures confirm that data transfer occurs every 1 minute as planned in the program. The sensor node is designed to go into sleep mode when it is not actively collecting, processing and sending data.

Node power consumption was measured based on the voltage and current (using the INA219 current sensor). The sleep time on the sensor node is set for 8 seconds. Table 6 shows that when the nodes were sleeping, nodes 1, 2, 3, and 4 consume average power (in mW) of 21.43, 22, 30.4, and 30.13, respectively. Meanwhile, when the nodes were actively sending data, nodes 1, 2, 3, and 4 consume average power (in mW) of 90, 84, 87, and 90, respectively. In this case, distance of 1 meter was still applied. Longer distance may cause more power consumption. The nodes in send mode consume more power than in sleep mode.

A1

	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	time:	00:27:25	node id:	3	temperature:	27.3	humidity:	95	soil moist level:	0	soil moist volt:	2.79	battery volt:	3.36
2	time:	00:27:27	node id:	1	temperature:	26.9	humidity:	81	soil moist level:	1	soil moist volt:	2.77	battery volt:	3.77
3	time:	00:27:41	node id:	4	temperature:	27.4	humidity:	79	soil moist level:	1	soil moist volt:	2.84	battery volt:	3.75
4	time:	00:28:14	node id:	2	temperature:	26.5	humidity:	78	soil moist level:	2	soil moist volt:	2.8	battery volt:	3.71
5	time:	00:28:26	node id:	1	temperature:	26.9	humidity:	81	soil moist level:	1	soil moist volt:	2.78	battery volt:	3.78
6	time:	00:28:29	node id:	3	temperature:	27.2	humidity:	95	soil moist level:	0	soil moist volt:	2.79	battery volt:	3.36
7	time:	00:28:44	node id:	4	temperature:	27.4	humidity:	79	soil moist level:	1	soil moist volt:	2.84	battery volt:	3.75
8	time:	00:29:16	node id:	2	temperature:	26.5	humidity:	78	soil moist level:	2	soil moist volt:	2.8	battery volt:	3.71

Figure 13. Saved data in CSV file

```
MariaDB [Sensor_data]> SELECT * FROM SensorData WHERE no BETWEEN "622" AND "629";
+-----+--------------+---------+-------------+----------+-----------------+----------------+--------------+
| no  | reading_time | node_id | temperature | humidity | soil_moist_level | soil_moist_volt | battery_volt |
+-----+--------------+---------+-------------+----------+-----------------+----------------+--------------+
| 622 | 00:27:25     | 3       | 27.30       | 95.00    | 0               | 2.79           | 3.36         |
| 623 | 00:27:27     | 1       | 26.90       | 81.00    | 1               | 2.77           | 3.77         |
| 624 | 00:27:41     | 4       | 27.40       | 79.00    | 1               | 2.84           | 3.75         |
| 625 | 00:28:14     | 2       | 26.50       | 78.00    | 2               | 2.80           | 3.71         |
| 626 | 00:28:26     | 1       | 26.90       | 81.00    | 1               | 2.78           | 3.78         |
| 627 | 00:28:29     | 3       | 27.20       | 95.00    | 0               | 2.79           | 3.36         |
| 628 | 00:28:44     | 4       | 27.40       | 79.00    | 1               | 2.84           | 3.75         |
| 629 | 00:29:16     | 2       | 26.50       | 78.00    | 2               | 2.80           | 3.71         |
+-----+--------------+---------+-------------+----------+-----------------+----------------+--------------+
```

Figure 14. Saved data in database

Table 6. Average power consumption

No	Mode	Node	Average Voltage (V)	Average Current (mA)	Average Power (mW)
1	Sleep	1	3.82	5.61	21.43
2		2	3.77	5.96	22.00
3		3	3.7	8.31	30.4
4		4	3.75	7.97	30.13
5	Send	1	3.76	24.25	90.00
6		2	3.56	23.4	84.00
7		3	3.47	25.4	87.00
8		4	3.55	25.35	90.00

4. CONCLUSION

WSN based on nRF24L01+ has been proposed and examined experimentally. The sensor nodes successfully sent and the sink node successfully received, processed, saved the data. The prototype can work properly with limited sensors and distance. Mesh topology is considered more suitable for this condition because of its dynamic network address. Advanced research to improve performance of the WSN with longer distance and better quality sensors for more agricultural parameters is considered to be future work. Human interface to display the data on smartphone or personal computer and control system are also required for further development. Solar panel based battery charger for sensor node will also be developed in the future.

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REFERENCES

[1] D. Thakur, Y. Kumar, A. Kumar, and P. K. Singh, “Applicability of wireless sensor networks in precision agriculture: a review,” *Wireless Personal Communications*, vol. 107, pp. 471–512, Apr. 2019, doi: 10.1007/s11277-019-06285-2.

[2] M. Srbinovska, C. Gavrovski, V. Dimcev, A. Krkoleva, and V. Borozan, “Environmental parameters monitoring in precision agriculture using wireless sensor networks,” *Journal of Cleaner Production*, vol. 88, pp. 297-307, Feb. 2015, doi: 10.1016/j.jclepro.2014.04.036.

[3] A. Abdollahi, K. Rejeb, A. Rejeb, M. M. Mostafa, and S. Zailani, “Wireless sensor networks in agriculture: insights from bibliometric analysis,” *Sustainability*, vol. 13, no. 21, p. 12011, 2021, doi: 10.3390/su132112011.

[4] S. A. Kumar and P. Ilango, “The impact of wireless sensor network in the field of precision agriculture: a review,” *Wireless Personal Communications*, vol. 98, no. 1, pp. 685–698, Jan. 2018, doi: 10.1007/s11277-017-4890-z.

[5] C. D. Moreno-Moreno, M. Brox-Jiménez, A. A. Gersnoviez-Milla, M. Márquez-Moyano, M. A. Ortiz-López, and F. J. Quiles-Latorre, “Wireless sensor network for sustainable agriculture,” *Environment, Green Technology, and Engineering International Conference*, vol. 2, p. 1302, Oct. 2018, doi: 10.3390/proceedings2201302.

[6] S. K. Dhillon, C. Madhu, D. Kaur, and S. Singh, “A review on precision agriculture using wireless sensor networks incorporating energy forecast techniques,” *Wireless Personal Communications*, vol. 113, pp. 2569–2585, Apr. 2020, doi: 10.1007/s11277-020-07341-y.

[7] R. Prodanović *et al.*, “Wireless sensor network in agriculture: model of cyber security,” *Sensors*, vol. 20, no. 23, pp. 1-22, Nov. 2020, doi: 10.3390/s20236747.

[8] F. Muzafarov and A. Eshmurado, “Wireless sensor network based monitoring system for precision agriculture in Uzbekistan,” *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 17, no. 3, pp. 1071-1080, Jun. 2019, doi: 10.12928/TELKOMNIKA.v17i3.11513.

[9] D. D. K. Rathinam, D. Surendran, A. Shilpa, A. S. Grace, and J. Sherin, “Modern Agriculture Using Wireless Sensor Network (WSN),” *2019 5th International Conference on Advanced Computing & Communication Systems (ICACCS)*, Coimbatore, India, 2019, pp. 515-519, doi: 10.1109/ICACCS.2019.8728284.

[10] D. Ardiansyah, A. S. M. Huda, Darusman, R. G. Pratama, and A. P. Putra, “Wireless sensor network server for smart agriculture optimatization,” *IOP Conference Series: Materials Science and Engineering*, vol. 621, pp. 30-31, 2019, doi: 10.1088/1757-899X/621/1/012001.

[11] G. I. Hapsari, G. A. Mutiara, L. Rohendi, and A. Mulia, “Wireless sensor network for monitoring irrigationusing XBeeProS2C,” *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 9, no. 4, pp. 1345–1356, Aug. 2020, doi: 10.11591/eei.v9i4.1994.

[12] Y. L. K. Macayana *et al.*, “Internet of things-based indoor smart hydroponics farm monitoring system,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 2, pp. 2326-2339, Apr. 2023, doi: 10.11591/ijece.v13i2.pp2326-2339.

[13] P. Musa, H. Sugeru, and E. P. Wibowo, “Wireless sensor networks for precision agriculture: A Review of NPK Sensor Implementations,” *Sensors*, vol. 24, no. 1, pp. 1-14, 2024, doi: 10.3390/s24010051.

[14] R. Madhumathi, T. Arumuganathan, and R. Shruthi, “Soil NPK and moisture analysis using wireless sensor networks,” In *2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Jul. 2020, pp. 1–6, doi: 10.1109/ICCCNT49239.2020.9225547.

[15] F. Khelifi, “Monitoring system based in wireless sensor network for precision agriculture,” *Internet of Things (IoT). Springer*, pp. 461–472, 2020, doi: 10.1007/978-3-030-37468-6_24.

[16] P. Rajak, A. Ganguly, S. Adhikary, and S. Bhattacharya, “Internet of things and smart sensors in agriculture: scopes and challenges,” *Journal of Agriculture and Food Research*, vol. 14, pp. 1-13, Sep. 2023, doi: 10.1016/j.jafr.2023.100776.

[17] M. Dhanaraju, P. Chenniappan, K. Ramalingam, S. Pazhanivelan, and R. Kaliaperumal, “Smart farming: internet of things (IoT)-based sustainable agriculture,” *Agriculture*, vol. 12, p. 1745, Oct. 2022, doi: 10.3390/agriculture12101745.

[18] S. H. Yang, “Wireless sensor networks principles, design and applications,” *Signals and Communication Technology (SCT)*, Springer-Verlag London, 2014, doi: 10.1007/978-1-4471-5505-8.

[19] S. Soijoyo and A. Ashari, “Analysis of zigbee data transmission on wireless sensor network topology,” *International Journal of Advanced Computer Science and Applications (IJACSA)*, vol. 8, no. 9, pp. 145-151, 2017, doi: 10.14569/IJACSA.2017.080921.

[20] F. Kiani and A. Seyyedabbasi, “Wireless sensor network and internet of things in precision agriculture,” *International Journal of Advanced Computer Science and Applications (IJACSA)*, vol. 9, no. 6, pp. 99-103, 2018, doi: 10.14569/IJACSA.2018.090614.

[21] S. N. Shylaja and M. B. Veena, “Real-time monitoring of soil nutrient analysis using WSN,” *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, Chennai, India, 2017, pp. 3059-3062, doi: 10.1109/ICECDS.2017.8390018.

[22] M. Majid *et al.*, “Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: a systematic literature review,” *Sensors*, vol. 22, no. 6, p. 2087, Mar. 2022, doi: 10.3390/s22062087.

[23] F. Zijie, M. A. Al-Shareeda, M. A. Saare, S. Manickam, and S. Karuppayah, “Wireless sensor networks in the internet of things: review, techniques, challenges, and future directions,” *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 31, no. 2, pp. 1190-1200, Aug 2023, doi: 10.11591/ijeecs.v31.i2.pp1190-1200.

[24] K. Bajaj, B. Sharma, and R. Singh, “Integration of WSN with IoT Applications: A Vision, Architecture, and Future Challenges,” In *Integration of WSN and IoT for Smart Cities*, pp. 79-102, March 2020, doi: 10.1007/978-3-030-38516-3_5.

[25] N. Semiconductor, “nRF24L01+ single chip 2.4GHz transceiver,” *Nordic Semiconductor*, [Online], Available: https://www.sparkfun.com/datasheets/Components/SMD/nRF24L01Pluss_Preliminary_Product_Specification_v1_0.pdf, (Accessed: Jan. 15, 2024).

[26] A. C. Bento, L. A. T. Mantovani, N. Santos, and S. J. G. Da Silva, “A Data Transmission Survey with NodeMCU12e with Motor Shield and Nextion + NRF24L01,” *2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Kanpur, India, 2019, pp. 1-6, doi: 10.1109/ICCCNT45670.2019.8944865.

[27] A. C. Bento, E. M. L. da Silva, and E. M. de Souza, “An Experiment with NRF24L01+ and Arduino Pro Micro Data Transmission for IoT,” *2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Kanpur, India, 2019, pp. 1-6, doi: 10.1109/ICCCNT45670.2019.8944813.

[28] Z. Abidin, E. Maulana, M. Y. Nurrohman, F. C. Wardana, and Warsito, “Real Time Monitoring System of Drinking Water Quality Using Internet of Things,” *2022 International Electronics Symposium (IES)*, Surabaya, Indonesia, 2022, pp. 131-135, doi: 10.1109/IES55876.2022.9888400.

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