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Range Characterization of a LoRa-Equipped Decentralized Wireless Sensor Network for Monitoring Forest Areas

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***Abstract*— A decentralized four-node LoRa wireless sensor network was developed and tested to characterize its performance in a forested environment in terms of RSSI, SNR, and packet error rate. Each ESP32-based node transmitted temperature (BMP280), GPS, and time data, while a receiver-rotation scheme ensured controlled, non-overlapping transmissions. The system demonstrated full coverage of Arroceros Forest Park, with performance variations primarily driven by distance, antenna height, and foliage. Regression analysis from controlled two-node experiments showed that RSSI is strongly predicted by these factors (R^2 = 0.8468) and SNR to a lesser extent (R^2 = 0.4602), with all models statistically significant ($p < 0.001$). Distance had the strongest influence on RSSI, while foliage introduced the largest degradation in SNR and PER. In the four-node deployment, asymmetric link behavior and higher PER values were consistently observed on foliage-obstructed paths and on longer links, confirming the regression trends and highlighting foliage as the dominant source of performance loss. Overall, the measured PER, SNR, and RSSI align with the propagation behavior predicted by the models, validating the network's reliability across the test area.**

Keywords—decentralized network, forest monitoring, LoRa, receiver rotation, wireless sensor network

I. Introduction

Wireless sensor networks (WSNs) are a rapidly growing field in the Internet of Things (IoT) due to their utility and versatility in various monitoring applications. Monitoring forests is important for their preservation, maintenance, or restoration. Even today, the use of WSNs for forest monitoring is not a widely established practice since heavy foliage and plant growth can interfere with the signals sent throughout the network. This gap can be addressed by characterizing the range of a wireless sensor network deployed in such an environment to inform future applications on how to implement them appropriately.

Previous research has explored techniques like satellite imagery, drone surveillance, and sensor-based technologies to monitor forests. Meanwhile, a ground-based wireless sensor network using ESP32 Wi-Fi Mesh protocol can have nodes spaced up to 100 meters apart while maintaining acceptable signal loss [1]. The use of Long Range (LoRa) transmission allows for the deployment of long-range ground-based sensor nodes whose coverage can surpass that of systems using Wi-Fi or Bluetooth, although its transmission quality is ideally measured in open spaces with little interference [2].

However, there is a lack of research focusing on the range characteristics of LoRa when deployed in an area with heavy foliage (dense volume of leaves or branches). This research will address that gap by creating a self-contained (independent or minimal need for human intervention), decentralized wireless sensor network by integrating the ESP32 microcontroller with a LoRa module and environmental sensors that can cover at least one hectare of forest area.

The main objective of this study is to characterize the range of a decentralized monitoring network across at least one hectare of forest area. Specifically, the study aims: (1) to produce four independent sensor nodes that can be connected to form a decentralized wireless sensor network; (2) to determine optimum antenna height and distance between nodes by measuring the quality of signal transmission between each node through received signal strength index (RSSI), signal-to-noise ratio (SNR), and packet error rate (PER); (3) to test the transmission of data collected from the temperature sensor; and (4) to evaluate the range and coverage area of the network using quality of signal transmission of sensor data between nodes.

Conducting this study can benefit concerned institutions and government agencies by making it easier to determine where sensors should be placed in the deployment of a wireless monitoring system for inaccessible forest areas. Local forest authorities can use the decentralized network as an alternative to current forest monitoring methods to address limitations effectively. Surveyors who face logistical barriers that come with remote and hard-to-reach regions can also be assisted by this network.

Due to limited financial resources, only four nodes will be developed to test the nodal capabilities of the network, which constrains the ability to fully assess scalability across a larger number of nodes. Moreover, the study will not compare the performance of a decentralized network topology with a centralized one. The research will be conducted in a forest area with heavy foliage.

II. Review of Related Literature

A. Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are a good fit for monitoring agricultural environments since they are relatively easy to maintain and scale. The study of [1] deployed a WSN configured in a centralized network topology whose nodes were constructed with an Arduino and ESP32 setup. The study only investigated RSSI versus distance between nodes and found that nodes could be placed 100m apart while maintaining acceptable RSSI levels. [2] focused on testing the range characteristics of the LoRa module using a centralized network topology. Their setup was tested indoors and considered RSSI, SNR, and packet loss rate. Losses between nodes were attributed to obstruction of line-of-sight (LOS). Likewise, this study measured signal quality in terms of RSSI, SNR, and PER.

If applied to monitoring forest health, the ideal approach is to deploy a network of multi-sensor nodes to provide a holistic view of the condition surrounding environment over a wide geographic area [3], [4]. Building such nodes based on an ESP32+LoRa combination is popular due to its energy-efficiency, scalability, cost-effectiveness, and ability to provide real-time monitoring [1], [5]. This study employed a similar approach for prototype design; however, only a single sensor module was used since the primary objective is range characterization of the network using the sensor data.

B. Decentralized Networks

Unlike centralized systems that rely on a single point of control, decentralized networks distribute responsibility across multiple nodes, thereby reducing the risk of total system failure in case one node malfunctions. A peer-to-peer (P2P) network allows scalability and fault tolerance [6]. [4] used the CHORD protocol to enable rapid data lookup and transfer between six nodes, achieving logarithmic search time when requesting data within the network. Unlike this study, it did not explore the capability of a LoRa based decentralized network to support continuous streams of data to populate a live webserver-based dashboard. Hence, Chord is best suited for intermittent data searches and not real-time monitoring.

C. LoRa in Sensor Networks

LoRa technology uses chirp spectrum (CSS) modulation, which is a modified form of frequency shift keying where data is encoded onto the changing frequency of the carrier signal (called chirp). Its range is dependent on output power, bandwidth, and spreading factor (SF), which is the number of chirps per symbol normalized to log base 2. The SF of a LoRa module can be set from 7 to 12, with SF12 being the easiest to decode at the receiver. Higher SF corresponds to a better range and reduced (PER) at the cost of data rate and transmission time [7]. The opposite is true for lower SF, making them ideal for applications where speed is prioritized over range.

The SF can be dynamically adjusted to maximize the throughput of a network. [8] explored this using several LoRa nodes communicating at 2.4GHz. Their setup involved a master LoRa board continuously pinging sensor nodes and changing the SF based on their reply. In contrast, this study fixed the SF of all nodes at SF9 in consideration of the balance between range and transmission time, which is crucial for live data.

III. Methodology

This section outlines the design, implementation, and range characterization of the decentralized network to monitor forest health.

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A. *Conceptual Framework*

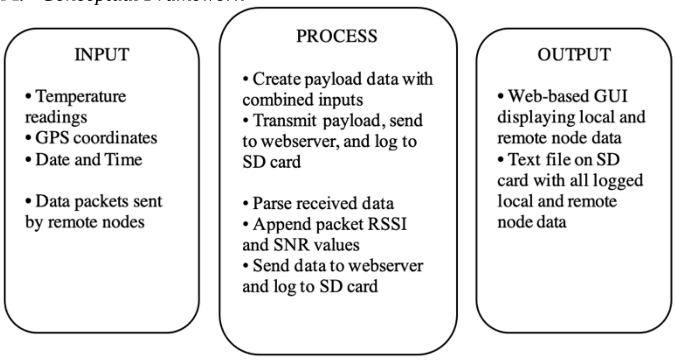

Fig. 1. Conceptual Framework

The framework of the study outlined in Figure (1) provides a structured approach to design, implement, and characterize the range of the proposed decentralized network. When a node was acting as a transmitter, its input was the temperature readings from the sensor module as well as information from the GPS and real-time clock modules. It transmitted them to other nodes and logged them onto an SD card. When it was acting as a receiver, it captured available packets from other nodes and measured their RSSI and SNR values by logging the data and displaying it on the webserver.

B. *System Process Flow*

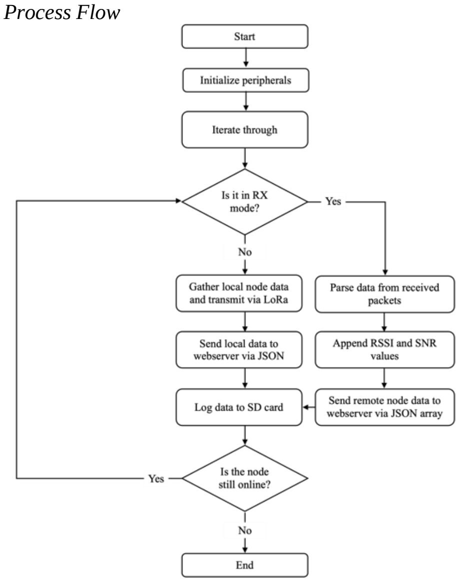

Fig. 2. System Process Flow

Figure (2) shows the process flow in each node. First, the node determined if it was in transmitter or receiver mode based on an algorithm for receiver rotation logic. During transmitter mode, the surrounding temperature readings were taken from the BMP280 sensor module. GPS data, date and time, and Node ID are appended to this before transmission and logging. Meanwhile, in receiver mode, it listened for available packets from other nodes using the LoRa and logged them along with their RSSI and SNR values.

To evaluate the range and transmission capabilities of the system, the adjacent node-to-node distances and height of antennas were varied. The signal strength parameters were measured at each trial. Finally, the transmitted and received data were displayed using a web-based GUI accessible through any mobile device.

C. *Hardware Design*

The network featured four nodes where each one could act as either a transmitter or receiver. Each node consists of an ESP32 microcontroller, a BMP280 sensor module, a LoRa SX1278 transceiver with a 433 MHz monopole antenna, a NEO-6M GPS module, a DS3231 RTC module, a microSD card reader, and a 5V charging module for the battery. A printed circuit board was designed to hold the components and minimize physical wiring while preserving the integrity of high-speed digital signals in the circuit.

D. *Validation of Sensor Data*

The temperature data obtained from the sensor modules were compared with the readings from a digital ambient temperature sensor to serve as the control. This was used to calibrate the sensors based on the difference between their readings. Then, the validity of the sensor data transmitted during deployment was checked in terms of its mean absolute error (MAE) from the temperature readings taken from the control. The MAE was computed as:

$$MAE = \frac{1}{n}\sum_{k=0}^{n} \left|T_{control,k} - T_{sensor,k}\right|. \quad (1)$$

E. *Receiver Rotation Algorithm for Decentralization*

Since the network is decentralized, there should be no central node with higher authority to control the rest of the network. However, the fact that there is a webserver-based dashboard through which other devices can view the live node data in the network implies the need for nodes to see each other's data in near real time. The problem was enabling real-time data monitoring without a base station. This was solved using receiver rotation logic.

TABLE I. Receiver Rotation Matrix for Node Role

Step	Node 1	Node 2	Node 3	Node 4
1	1	1	0	0
2	0	0	1	1
3	1	0	1	0
4	0	1	0	1
5	1	0	0	1
6	0	1	1	0

Table I shows the receiver rotation matrix, a six-by-four matrix which contains the configuration of each node in the network as either receiver (called RX mode and assigned 1) or transmitter (called TX mode and assigned 0). The four columns correspond to nodes one to four, while the six rows contain the roles that each node will operate at each step. The node ID was fixed while a 1 Hz pulse from the RTC triggered the matrix to cycle through each step. Hence, each step lasts for one second. Consequently, there are two transmitting and two receiving nodes in each step, and the cycle lasts for six seconds. This configuration optimizes the tradeoff between nodes sending new data in TX mode and keeping the webserver dashboard updated in RX mode. Then, the time slot for TX mode was further divided in two so that each TX node will only transmit data in their assigned half-second. Figure (3) shows how each time slot was split to allow 480ms of airtime, which was sufficient for a spreading factor of 9, with a guard time slot of 40ms in between to prevent collision.

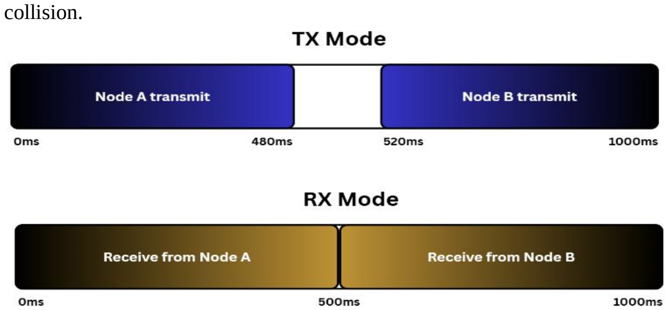

Fig. 3. Timing of transmission and reception of data per step

F. *Evaluation of Signal Quality*

During deployment in the testing area, each node was mounted on a tripod with an adjustable pole, allowing antenna heights from 1–2.5 m, as shown in Figure (4). Data collection was performed in three phases. In the first phase, signal quality between two nodes in direct line-of-sight (LOS) was measured at increasing distances (10–70 m) and varying antenna heights; the timestamps indicate the start and end of each measurement for a given distance-height combination, showing that each configuration was recorded sequentially over time. The second phase repeated the procedure for two nodes under foliage, the distances were calculated based on the recorded average GPS location. These distances vary in interval as data gathering was limited to the walkways constructed in the forest park. Finally, all four nodes were deployed at the corners of the park to evaluate full-area coverage. While the nodes are gathering data and logging the time, the researchers have timestamped the details of the height and distance of the nodes. This approach ensures a controlled, systematic measurement of RSSI and SNR across distances, heights, and environmental conditions, providing data that directly feed into the regression and PER analyses. The time intervals between measurements also helped account for temporal variations in the environment, such as pedestrian movement and

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transient interference, ensuring that the collected data accurately represent the network performance under realistic conditions.

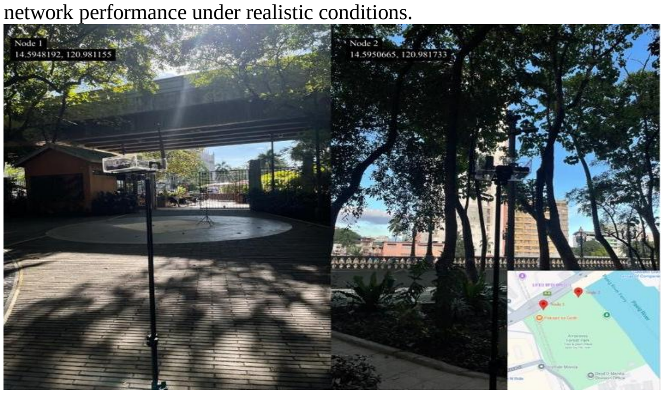

Fig. 4. Nodes at two different locations mounted on tripods in Arroceros Park

RSSI, SNR, and PER were used to quantify the signal quality between nodes at each configuration of inter-node distance and antenna height. Each packet received had corresponding RSSI and SNR values, both measured in decibels (dB). RSSI values between 0dB and -30dB were considered strong as these indicated little attenuation, while those below -80dB were considered weak. SNR values between 5dB and 10dB were considered good while those above 10dB indicated high reliability due to the significant difference in level between the signal and noise floor. The PER was obtained by getting the ratio of the number of packets that were received with errors to the total number of packets received during the observation period; Packet errors occurred as unidentified characters or incorrect identifiers in the logged data and were computed with

$$PER = \frac{no.of\ packets\ received\ with\ errors}{no.of\ packets\ received} * 100. \quad (2)$$

G. Statistical Treatment

The MATLAB code performs a comprehensive statistical analysis of wireless communication data by generating derived features such as polynomial terms, interaction terms, log/exponential transformations, and physics-based metrics like FSPL and two-ray models. To explain signal behavior, the code applies multiple regression models—including interaction-based [9], comprehensive polynomial [10], and stepwise-selected feature models [11], [12]—as validated by recent literature. Correlation analysis and feature engineering are used to enhance predictive power, supporting model design aligned with findings in [13] and [9]. The models are trained and validated using a 70–30 data split, and their accuracy is assessed using R^2 and adjusted R^2. This workflow reflects best practices in predictive modeling of RSSI and SNR and supports reproducible comparison of feature importance across signal environments.

Multiple polynomial regression was used to determine how much the RSSI and SNR values changed with respect to the distance between nodes (x_1), antenna height (x_2), foliage presence (x_3), distance squared (x_4), height squared (x_5), product between distance and antenna height (x_6), product between distance and presence of foliage (x_7), product between height and presence of foliage (x_8), free space path loss (x_9), two-ray ground reflection approximation (x_{10}). Note that Foliage is 1 when there is foliage present in between the two nodes, and 0 for nodes set up in LOS. This limits the prediction coefficient for foliage as the volume of foliage may vary depending on height, distance, and the layout of the forest park. FSPL estimates signal attenuation in a clear line-of-sight environment, increasing logarithmically with distance and frequency, and represents the idealized baseline loss. The Two-ray ground reflection approximation accounts for both the direct path and the reflected signal from the ground, showing that signal strength depends on both distance and antenna height.

IV. RESULTS AND DISCUSSION

This section shows the results of the evaluation of signal quality between nodes deployed in Arroceros Park based on the gathered RSSI, SNR, and PER. It also includes the interpretation of the data as well as statistical treatments applied to them to determine the relationship between signal quality parameters and configuration of the nodes in terms of distance and antenna height.

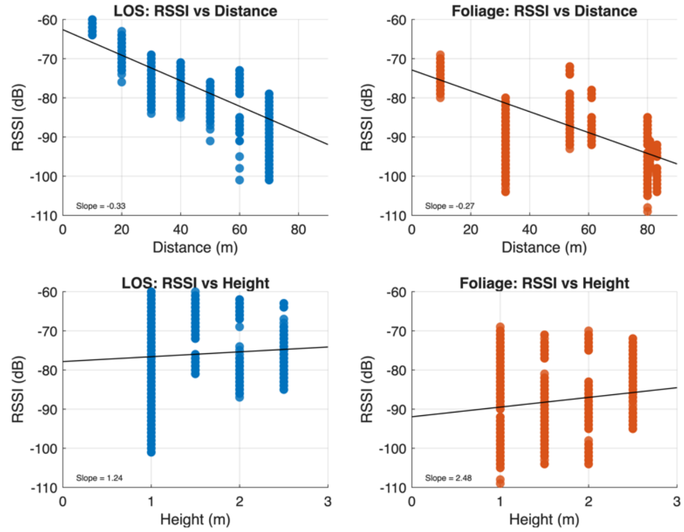

Fig. 5. RSSI vs. Distance & Height under LOS/foliage of 2 nodes

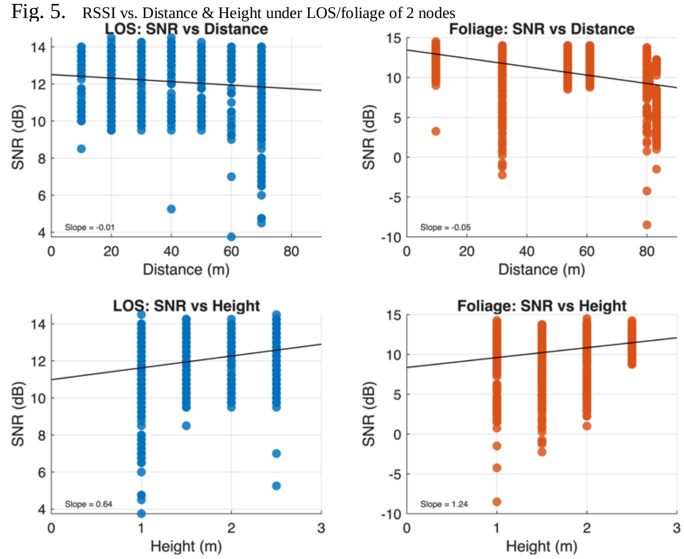

Fig. 6. SNR vs. Distance & Height under LOS/foliage of 2 nodes

The signal quality parameters between two nodes set up under LOS and foliage are depicted in Figures (5) and (6). Distance-based measurements showed negative slopes in LOS and foliage environments, confirming that signal strength degraded as distance increased. The attenuation was stronger for RSSI than SNR, and foliage introduced slightly more loss than LOS. In contrast, the height-based measurements showed positive slopes: as node height increased, both RSSI and SNR improved. The improvement of signal was more prevalent under foliage, where raising the antenna helped overcome obstruction and multipath effect. Height had a more significant effect on received signal power than on noise conditions. Foliage also consistently increased attenuation compared to LOS.

TABLE II. PACKET ERROR RATE IN TWO-NODE SET UP (N = 112)

Test ID	TX Node	RX Node	Distance (m)	Height (m)	Foliage Presence	PER (%)
1	1	2	10	2.5	0	3.57
2	1	2	20	1.5	0	2.22
3	1	2	70	2.5	0	1.69
4	2	1	10	1.5	0	3.45
5	2	1	70	2	0	1.23
6	1	2	61.01	1	1	1.43
7	1	2	61.01	1.5	1	1.04
8	1	2	61.01	2	1	3.53
9	1	2	80.78	1	1	1.25
10	1	2	80.78	2.5	1	2.5
11	1	2	83.19	1	1	0.6

12	1	2	83.19	2	1	0.51
13	1	2	83.19	2.5	1	1.52
14	2	1	9.67	2	1	1.01
15	2	1	31.82	1.5	1	1.92
16	2	1	80.78	1	1	1.56
17	2	1	83.19	1	1	1.87
18	2	1	83.19	1.5	1	0.57

Table II shows the PER between the same two nodes. Among the 112 total two-node setups, only 18 had non-zero Packet Error Rates (PER), indicating that the communication link was generally reliable across most configurations ranging from 10 m to 83 m distance and 1 m to 2.5 m antenna height. The entries show that more errors were seen under foliage than in LOS; however, the values remained low—all below 4%. PER appeared slightly higher in some short-distance cases (e.g., around 10 m to 20 m), suggesting that very close spacing may introduce multipath or interference effects. Under foliage, PER values remained low as well, typically around 0.5–2%. Still, certain height–distance combinations showed slight increases as with height = 2 m at 61.01 m. No clear monotonic trends emerged with respect to distance or height alone, but the presence of foliage did not consistently produce higher PER, implying that the system maintained good robustness even in obstructed environments. Overall, the data suggests that packet delivery performance was stable and resilient with only minor variations across different node heights, distances, and foliage conditions.

TABLE III. RSSI AND SNR REGRESSION MODELS FOR TWO-NODE SET UP

	RSSI Comprehensive Regression Model		**SNR Stepwise Regression Model**	
Parameter	**Value**			
R^2	0.8468		0.4602	
Standard Error	4.1253		1.9518	
F	2486.00		1003.76	
Significance F	0		2.354e-208	
Observations	8526		8526	
Predictor	**Coeff.**	**P-value**	**Coeff.**	**P-value**
Intercept	-725.95	5.36e-31	66.734	1.40e-238
Distance	2.4233	0	0.60668	2.35e-208
Height	-168.11	4.05e-69	-	-
Foliage	-20.178	0		
$Distance^2$	-0.018982	0	-0.00489	0
$Height^2$	26.007	3.05e-76	-	-
Distance*Height	0.11162	3.26e-236	-	-
Distance*Foliage	0.24756	0	-	-
Height*Foliage	0.285	0.10206	-	-
FSPL	22.448	4.54e-37	-1.0061	3.08e-172
Two-ray Approx.	-13.992	1.22e-56	-	-

The comprehensive RSSI regression model showed a strong fit with an R^2 of 0.8468 and an adjusted R^2 of 0.8466, indicating that the selected predictors explained most of the variation in RSSI. The standard error of 4.1253 and a highly significant F-statistic ($F = 2486$, $p < 0.001$) confirmed the model's reliability based on 8,526 observations. All predictors were statistically significant except for Height*Foliage. The environmental attenuation factor (Distance*Foliage) captured additional losses caused by obstacles like foliage, scaling proportionally with the amount of foliage and the distance that the signal traveled.

For the SNR stepwise regression model, R^2 was 0.4602 with a standard error of 1.9518, and an F-statistic of 1003.76 ($p < 0.001$), indicating a moderate fit. The stepwise selection retained only the most influential predictors—Distance, $Distance^2$, FSPL, and Distance*Height—while discarding less important variables. This simplified the model without sacrificing predictive power. These results highlight that RSSI was influenced by multiple environmental and propagation factors, while SNR can be effectively predicted with fewer, carefully chosen features. RSSI and SNR could be respectively predicted with the equations

$$y_{RSSI} = -725.95 + 2.4233x_1 - 168.11x_2 - 20.178x_3 - 0.018982x_4 + 26.007x_5 + 0.11162x_6 + 0.24756x_7 + 0.285x_8 + 22.448x_9 - 13.992x_{10} + 4.1253 \quad (3)$$

$$y_{SNR} = 66.734 + 0.60668x_1 - 0.00489x_4 - 1.0061x_9 + 1.9518. \quad (4)$$

TABLE IV. PACKET ERROR RATE IN FOUR-NODE SET UP ($N = 24$)

Test ID	**TX Node**	**RX Node**	**Distance (m)**	**Height (m)**	**Foliage Presence**	**PER (%)**
1	1	2	108	1.5	0	6.25
2	1	2	108	2	0	0.00
3	1	3	94	1.5	1	14.29
4	1	3	94	2	1	0.00
5	1	4	148	1.5	1	80.56
6	1	4	148	2	1	67.09
7	2	1	108	1.5	0	25.17
8	2	1	108	2	0	0.00
9	2	3	126	1.5	1	71.23
10	2	3	126	2	1	63.41
11	2	4	82	1.5	1	0.52
12	2	4	82	2	1	37.24
13	3	1	94	1.5	1	50.00
14	3	1	94	2	1	14.74
15	3	2	126	1.5	1	88.89
16	3	2	126	2	1	11.76
17	3	4	110	1.5	0	18.42
18	3	4	110	2	0	0.00
19	4	1	148	1.5	1	3.94
20	4	1	148	2	1	52.35
21	4	2	82	1.5	1	0.00
22	4	2	82	2	1	9.22
23	4	3	110	1.5	0	0.00
24	4	3	110	2	0	0.00

Table IV shows that distance, antenna height, and foliage remained the dominant factors affecting link performance—consistent with the predictors found significant in the two-node regression models. Increasing the antenna height from 1.5 m to 2 m almost always reduced PER, even when foliage was present as seen in Table B Test IDs one to 10 and 13 to 18. Foliage introduced major degradation, especially at medium to long distances (90–150 m), ranging in PER of 14.29–88.89%, confirming the strong negative impact of foliage found in the statistical models. In contrast, non-foliage links at moderate distances (<110 m) remained highly reliable, often reaching 0% PER which indicated stable connectivity when line-of-sight is preserved. The data also revealed asymmetric link behavior, where PER differed for the same physical path depending on which node was receiving (see Test IDs five and 19 with PERs of 80.56% and 3.94%, respectively). This is typical of wireless systems due to antenna orientation, multipath differences, and local interference, and supports the two-node finding that SNR is a better predictor of performance than raw RSSI. The relatively high Packet Error Rates may also be explained by the use of more nodes in the system, giving more chance for packet collisions between farther nodes. Overall, the four-node setup behaved exactly as the regression models predicted: distance and foliage exacerbated losses, antenna height improved reliability, and unobstructed mid-range links stayed stable. This alignment demonstrated that the four-node system operated within expected propagation behavior, hence validating its functional performance despite the more complex multi-node environment.

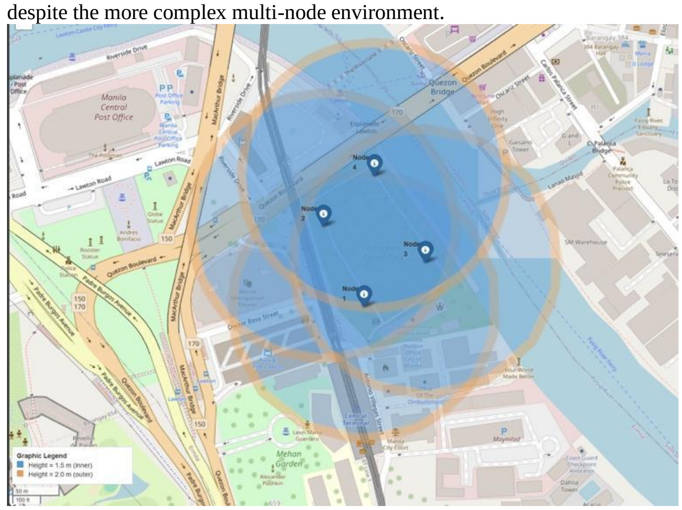

Fig. 7. Visualization of coverage area of the network

Figure (7) illustrates the coverage area of the four-node setup based on PER received at each node, highlighting that the nodes collectively provide connectivity across the entire Arroceros Forest Park. Specifically, their relative opacities correspond to the error rate, with more opaque sections meaning

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stronger links. Circles were chosen to represent the coverage area per node since the use of monopole antennas meant the nodes transmitted data in an omnidirectional manner. The blue circle indicates the reach of each node at an antenna height of 1.5 m while the orange circle is for the setup at a height of 2 m. As expected, the higher height had lower PER. Moreover, the radii of the circles were scaled so that for each one with one node at the center, all other nodes would be within its range. This is supported by the fact that no Test ID had a PER of 100%. Hence, the wireless sensor network was able to completely cover the target area.

TABLE V. OPTIMIZED DISTANCE AND HEIGHT BETWEEN TWO NODES

	Optimum Distance (m)	Optimum Height (m)
LOS	150	2
With Foliage	<125	2.5

Table V summarizes the optimum distances and antenna heights for reliable communication under different environmental conditions. In line-of-sight (LOS) scenarios, the optimum distance between nodes was 150 m with an antenna height of 2 m. This maximized coverage while maintaining low PER. In foliage-heavy areas, the optimum distance decreased to less than 125 m and a slightly higher antenna height of 2.5 m helped mitigate signal degradation caused by obstructions. While data could still be received at 100 m even with weak RSSI, PER increased significantly under foliage, indicating shorter spacing is necessary. Higher antenna heights improved reception in LOS conditions. But in dense foliage, benefits were only observed when obstruction was minimal. Excessively high placement may not yield additional gains. Therefore, setting antennas at 2 m for LOS and around 2.5 m for foliage, while adjusting node spacing according to the environment, would ensure optimal coverage and reliability.

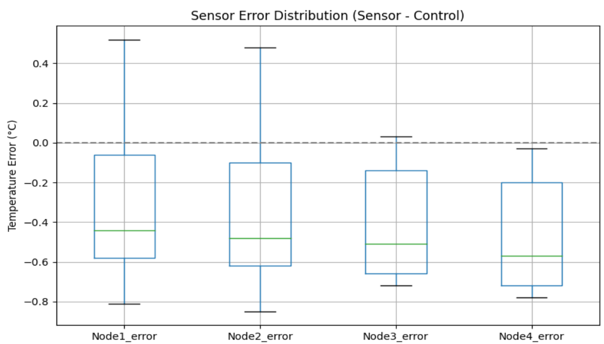

Fig. 8. Error distribution of temperature sensors

Figure (8) depicts the error distribution of each of the temperature sensors used by the nodes to collect data. All sensors drifted slightly below the true value, with the largest errors being between 0.6°C and 0.8°C below the mark. Node 1 had an MAE of 0.426, node 2 had 0.450, node 3 had 0.410, and node 4 had 0.468. As such, the sensor data being sent throughout the network were reliable and precise, though further accuracy could be attained through finer calibration.

V. CONCLUSION

This study characterized the range of a LoRa-equipped decentralized sensor network by examining the signal quality between nodes in terms of RSSI, SNR, and PER. In meeting its objectives, it found that: (1) a decentralized sensor network with four independent nodes can be successfully deployed using the algorithms and designs described in the methodology; (2) the optimum distance between two nodes is 150 m in LOS and <125 m in foliage, while the optimum antenna height is 2 m for LOS and 2.5 m for areas with foliage; (3) sensor data can be reliably transmitted between nodes to cover the entire Arroceros Park due to the consistent SNR values; and (4) the coverage area of the whole network can be visualized based on RSSI since it can be used to estimate the node's signal reach.

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