

Performance Evaluation of LoRa-Based Wireless Sensor Network for Smart Waste Bank Data Transmission

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Abstract - This study presents the design and performance evaluation of a LoRa-based Wireless Sensor Network (WSN) prototype for data transmission in a Smart Waste Bank system operating in a semi-urban environment. The proposed system adopts a hybrid network architecture, combining multi-hop communication among sensor nodes with a star topology for long-range transmission to a Raspberry Pi-based sink node. An ESP32 microcontroller integrated with a LoRa SX1278 module operating at 433 MHz is used to transmit waste volume and activity data with low power consumption. Unlike prior studies that predominantly focus on generic LoRa performance evaluation, this research provides a contextual and application-driven assessment of LoRa-based WSN communication tailored to community-scale Smart Waste Bank operations under non-line-of-sight conditions. System performance was evaluated using RSSI, SNR, and PDR at transmission distances ranging from 10 m to 1000 m. Experimental results show that RSSI decreases from -56 dB to -112 dB and SNR from 6.3 dB to 1.0 dB as distance increases, while the system maintains reliable communication with an average PDR of 97% up to 800 m. Distinct from existing LoRa performance studies, this work explicitly integrates a hybrid multi-hop and star WSN topology within a real-world smart waste bank deployment, providing empirical communication benchmarks that are directly applicable to community-scale IoT implementations rather than controlled or generic test scenarios.

Keywords: LoRa-based wireless sensor network; smart waste bank system; hybrid multi-hop and star topology; non-line-of-sight communication performance; community-scale IoT implementation.

I. INTRODUCTION

Urban waste management faces serious challenges, particularly in communities with limited human resources and infrastructure. In RT03/RW01, Arjosari Village, Malang City, waste collection is handled by a

single worker serving 58 households, often resulting in waste accumulation, collection delays, and adverse impacts on the environment and public health. One of the community-based initiatives that has emerged is the waste bank program, a system that allows residents to deposit inorganic waste with economic value while raising environmental awareness [1-3].

However, conventional waste bank operations still face obstacles in monitoring waste volume. Personnel must manually inspect containers, which is inefficient and leads to delayed waste collection. The integration of the Internet of Things (IoT) through a Wireless Sensor Network (WSN) offers a promising solution: waste level or volume data can be automatically monitored from sensor nodes and transmitted to a central system for data-driven decision-making [1-2, 4-6]. Studies on smart waste systems show that monitoring bin fill levels can reduce truck trips and improve collection scheduling accuracy [1, 7-9].

A key challenge in implementing WSNs lies in selecting a reliable, energy-efficient communication technology that does not depend on dense network infrastructure (e.g., Wi-Fi or GSM). LoRa (Long Range) provides long-range communication with low power consumption, making it suitable for IoT applications in both urban and semi-urban environments [10-14]. Trials of LoRa/LoRaWAN deployment in various cities have demonstrated its reliability in urban and suburban settings, with trade-offs between spreading factor, bandwidth, coding rate, and LOS/NLOS conditions [12-15]. Meanwhile, recent studies also highlight the impact of vegetation and physical obstructions that can degrade packet delivery and signal quality, emphasizing the importance of node and antenna placement [11].

This study focuses on evaluating the performance of LoRa as a data transmission medium within a WSN to support smart waste bank systems. The sensor node, based on an ESP32 microcontroller integrated with an ultrasonic sensor (for volume measurement) and a PIR

sensor (for user activity detection), transmits data to a Raspberry Pi sink node via a LoRa RA-02 SX1278 module (433 MHz). The data are stored in a database and visualized through a web interface. This approach is expected to enhance operational efficiency, reduce collection delays, and strengthen the sustainability of waste bank programs [1, 7, 16-18]. Furthermore, empirical evidence from LoRa-based studies on smart waste and environmental monitoring indicates multi-kilometer transmission ranges with low power consumption, reinforcing the importance of contextual performance evaluation (distance, obstruction, node density, and radio parameters) to enable replication of this solution in Indonesia’s urban areas [1, 7, 12, 13, 15, 19, 20].

Overall, prior studies on LoRa-based wireless sensor networks for smart waste management and environmental monitoring have largely focused on generic urban deployments, LoRaWAN-based infrastructures, or simulation-based evaluations, with most implementations relying on single-hop star topologies. While these studies provide valuable insights into LoRa communication characteristics, they rarely examine hybrid network architectures or address practical deployment constraints faced by community-scale waste bank systems, such as limited infrastructure, low operational cost, and non-line-of-sight conditions. In contrast, the present study differs by empirically evaluating a hybrid multi-hop and star LoRa-based WSN within a real-world Smart Waste Bank deployment in a semi-urban environment. By emphasizing contextual performance factors, including transmission distance, environmental obstructions, and practical operational conditions, this work provides application-driven benchmarks that complement existing studies and support replicable community-based IoT implementations.

II. METHOD

This study employs an applied experimental research method aimed at evaluating the performance of a LoRa-

based WSN in data transmission for a smart waste bank system. The experimental approach was chosen to obtain empirical data on LoRa communication performance, including signal strength, transmission success rate, and sensor reading accuracy under real environmental conditions. The research was conducted by developing an IoT-based system prototype consisting of sensor nodes, a LoRa communication module, and a Raspberry Pi-based sink node. System performance evaluation was carried out by measuring parameters such as RSSI, SNR, PDR, and sensor accuracy in transmitting waste volume data to the central system. The Methodology section has been revised to improve clarity and reproducibility. An explicit flowchart describing the experimental testing sequence has been added. In addition, a dedicated subsection detailing the LoRa communication parameters (spreading factor, bandwidth, coding rate, and transmission power) has been included. The role of the hybrid multi-hop and star topology has also been clarified, emphasizing that performance evaluation focuses on the long-range LoRa communication link. Each measurement at a given distance was repeated three times, and the average values were used for analysis. Due to the limited number of repetitions, statistical dispersion metrics such as standard deviation were not explicitly reported. For the PDR evaluation, a total of 100 data packets were transmitted in each trial at every transmission distance. The PDR value was calculated as the ratio between the number of successfully received packets at the sink node and the total number of transmitted packets. Accordingly, the quantitative performance metrics reported in this study (RSSI, SNR, and PDR) are measured exclusively on the long-range LoRa communication link between the sensor node and the Raspberry Pi sink node, while the multi-hop segment is implemented to support local data aggregation and is not separately evaluated in terms of communication performance.

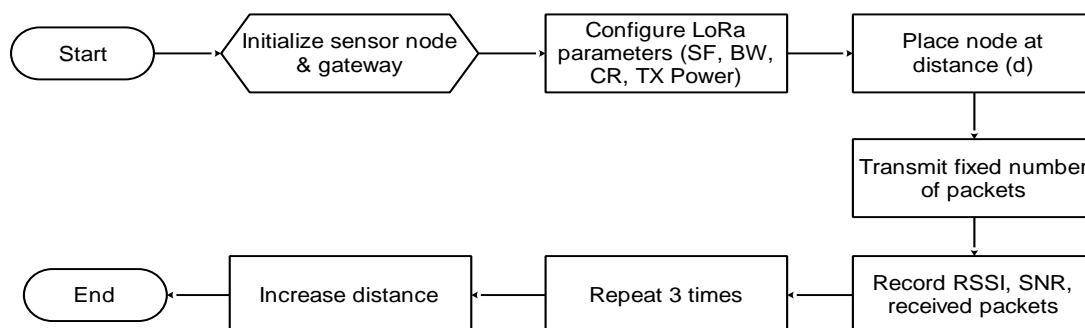


Fig. 1 Flowchart of the experimental testing procedure

A. System Design

The system developed in this study consists of several sensor nodes interconnected through a LoRa (Long Range) network to a Raspberry Pi sink node. The Raspberry Pi functions as a data collector (gateway) as well as a bridge between the local sensor system and the web-based server. Measurement data from the sensor nodes are transmitted wirelessly using the LoRa SX1278 (433 MHz) module, then forwarded to the database server and visualized through a monitoring website. The overall system block diagram is shown in Fig. 2.

Based on Fig. 1, the Raspberry Pi functions as both the sink node and the gateway that collects data from Node 3 and forwards it to the database server via an internet connection. The stored data can then be accessed through a web interface, allowing users to monitor the system in real time from a remote location. In terms of network topology, the system employs a combination of a multi-hop topology for inter-node communication (Node 1 → Node 2 → Node 3 using ESP) and a star topology between Node 3 and the sink node (Raspberry Pi via LoRa). This approach enables efficient communication and power savings while simultaneously extending the system’s coverage range. The proposed system adopts a hybrid network architecture that combines multi-hop communication among sensor nodes and a star topology for long-range transmission to the sink node. This architectural choice is motivated by the need to extend coverage while maintaining low power consumption and minimal infrastructure requirements, which are critical for community-scale Smart Waste

Bank deployments. Unlike conventional single-hop LoRaWAN implementations, the hybrid approach enables flexible node placement and supports practical deployment in semi-urban environments.

B. Hardware Design

The hardware design is a crucial stage in developing a LoRa-based WSN system for smart waste bank applications. The block diagram shown in Fig. 3 illustrates the relationship among the main components of the sensor node, which consists of input sensors, a microcontroller, actuator components, and a wireless communication module.

In general, the sensor node functions to detect user activity and measure waste volume, then transmit the measurement data to the sink node via LoRa communication. The node integrates sensing, local control, and wireless data transmission to support real-time monitoring in a smart waste bank system.

On the input side, the system employs a Passive Infrared (PIR) sensor to detect the presence or movement of users near the waste bin and an HC-SR04 ultrasonic sensor to measure the height of the waste pile inside the bin based on ultrasonic wave reflection. Two pairs of PIR and ultrasonic sensors are used for two separate waste bins (e.g., organic and inorganic), each operating independently but controlled by a single ESP32 microcontroller. When user presence is detected, the ESP32 activates a relay-controlled servo motor to automatically open the waste bin lid, which closes again after a predefined delay or when no motion is detected.

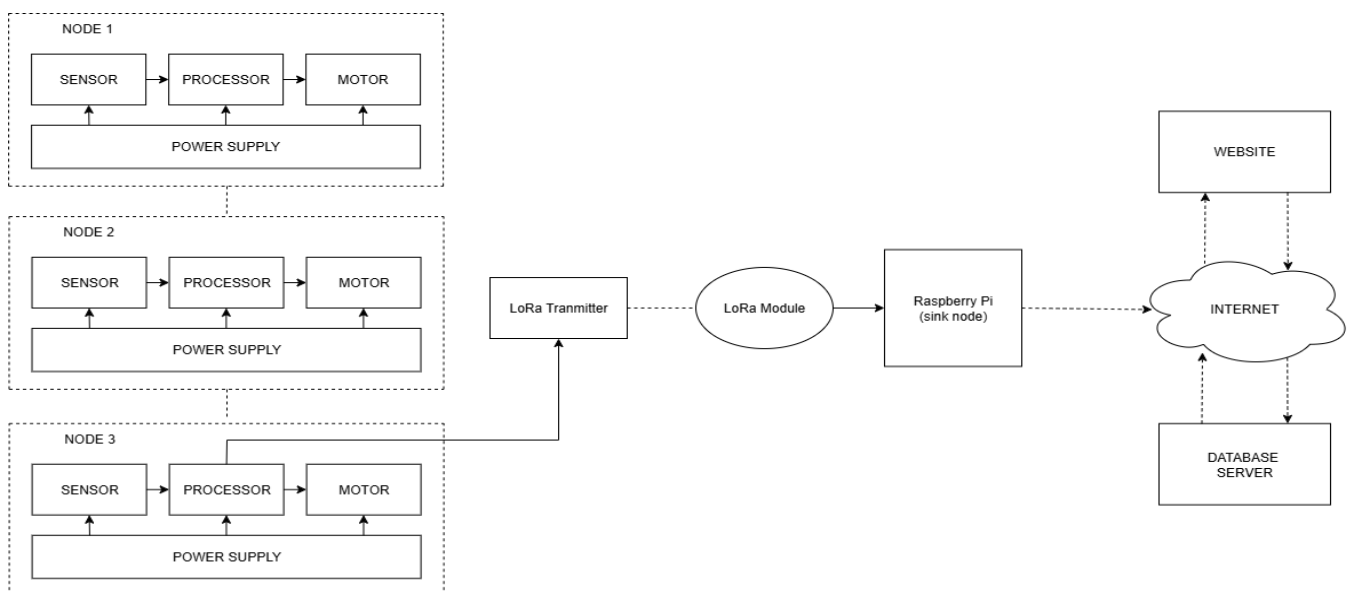


Fig. 2 Overall system design

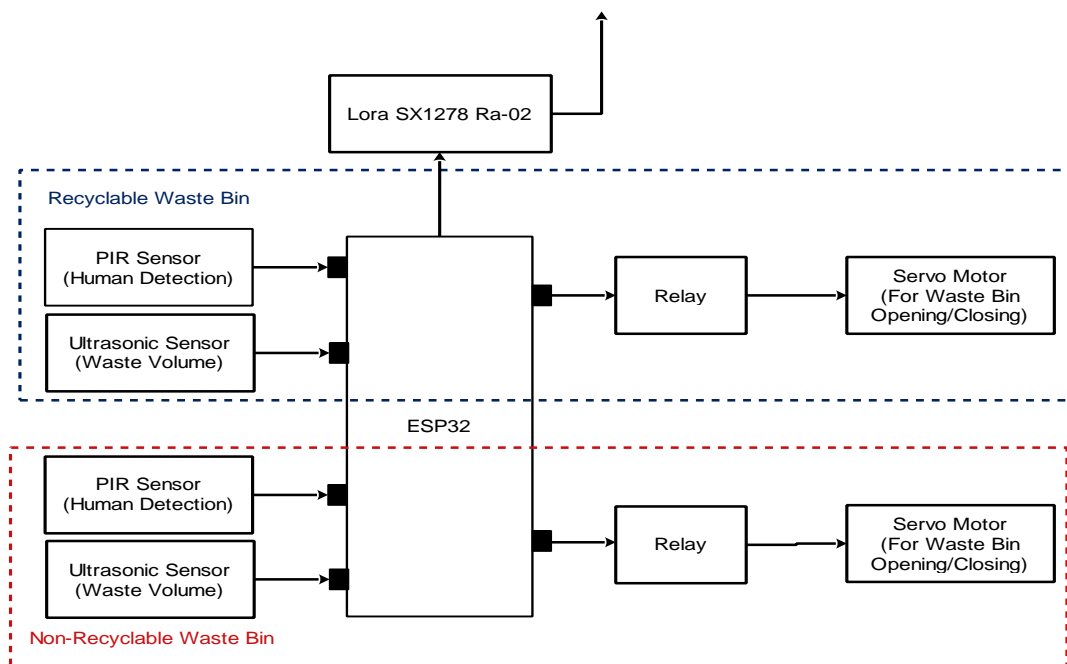


Fig. 3 Block diagram of the ESP32 and LoRa SX1278-Based sensor node

Wireless data transmission is handled by a LoRa SX1278 module operating at 433 MHz, which communicates with the ESP32 via the Serial Peripheral Interface (SPI). LoRa technology is selected for its long-range communication capability and low power consumption, making it suitable for community-scale Internet of Things (IoT) deployments. The entire system is powered by a Li-ion 18650 battery that provides a stable voltage supply for the ESP32, sensors, and actuators, enabling long-term operation without frequent recharging.

Overall, this hardware design forms an independent sensor node capable of data acquisition, mechanical control, and automated information transmission via the LoRa network. These sensor nodes communicate with the Raspberry Pi sink node, which collects all field data and forwards them to a database server for real-time monitoring through a Laravel-based web interface.

C. Component Pin Configuration

The pin configuration between the ESP32 and the LoRa SX1278 is presented in Table I. This setup ensures proper connections between the microcontroller and the communication module, allowing data to be transmitted efficiently.

D. Physical System Design

The physical system design stage illustrates the actual form and dimensions of the smart waste bin developed in this study. The physical design of the device is shown in Fig. 4, which presents the front and top views of the

smart waste bank system featuring two main compartments: one for recyclable waste and another for non-recyclable waste.

The smart waste bin is designed with a total width of 60 cm, a height of 45 cm, and a depth of 30 cm, using an aluminum pipe frame to ensure strength while maintaining a lightweight structure. At the top of each compartment, an HC-SR04 ultrasonic sensor is installed to measure the volume or height of the waste pile inside the bin in real-time using the principle of ultrasonic wave reflection. Two ultrasonic sensors are positioned parallel at a distance of 60 cm to ensure each sensor has an optimal reflection area without interference.

A Passive Infrared (PIR) sensor is placed at the center front of the bin to detect user movement when approaching. When the PIR sensor detects human presence, the ESP32 microcontroller sends a control signal to the relay to activate the servo motor, which automatically opens the bin lid. After the user moves away or after a certain delay, the servo motor closes the lid again to maintain cleanliness and energy efficiency.

In addition to functional aspects, the physical design is made to be user-friendly and suitable for community environments. The two compartments (recyclable and non-recyclable) are placed side by side to facilitate waste sorting. The central placement of the PIR sensor ensures that the detection area covers the entire front side of the device, while the ultrasonic sensors positioned on top provide an optimal distance from the waste surface to ensure accurate distance measurement.

TABLE I
PIN CONFIGURATION BETWEEN LORA RA-02 SX1278 AND ESP32

Component Name	Pinout	Connection Purpose (Destination)
LoRa RA-02 SX1278	VCC	3V3 / ESP32
	GND	GND / ESP32
	SCK	GPIO18 / ESP32
	MISO	GPIO19 / ESP32
	MOSI	GPIO23 / ESP32
	NSS (CS)	GPIO5 / ESP32
	RESET (RST)	GPIO14 / ESP32
	DIO0	GPIO26 / ESP32

E. LoRa Communication Parameters

The LoRa communication parameters configured in the experimental procedure (Fig. 1) are summarized in Table 2. The LoRa SX1278 module operated at a carrier frequency of 433 MHz with fixed communication parameters throughout the experiments to ensure measurement consistency and reproducibility. The spreading factor, bandwidth, coding rate, and transmission power were configured prior to testing and maintained constant for all distance variations. This configuration allows the observed variations in RSSI, SNR, and PDR to be attributed primarily to transmission distance and environmental conditions rather than dynamic parameter changes.

III. RESULT AND DISCUSSION

After completing the hardware and software design process, the LoRa-based WSN system for the Smart Waste Bank application was successfully implemented in its entirety. The result of the system implementation is shown in Fig. 5.

The system testing was conducted in RT 03/RW 01, Arjosari Village, Blimbing District, Malang City, which features semi-urban characteristics with a combination of open and obstructed NLoS areas. The testing focused on evaluating the performance of LoRa communication in relation to data transmission distance based on three main parameters:

- 1) RSSI (Received Signal Strength Indicator) – measures the strength of the received signal.
- 2) SNR (Signal-to-Noise Ratio) – measures signal quality against environmental interference.
- 3) PDR (Packet Delivery Ratio) – measures the success rate of data packet transmission.

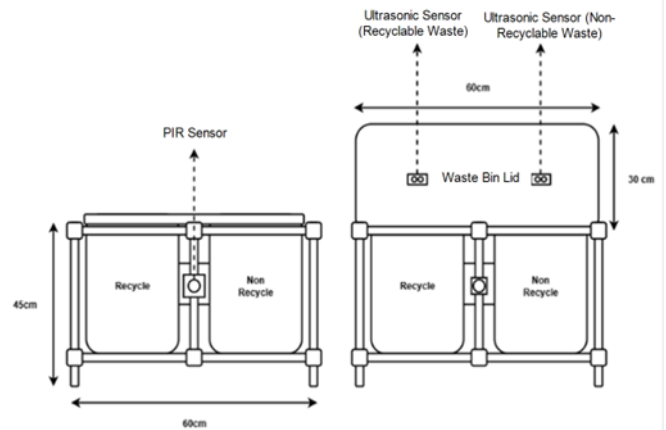


Fig. 4 Physical design of a smart waste bin with pir and ultrasonic sensors

Distance variations for testing ranged from 10 m to 1000 m, with three repetitions at each distance, and the average results were used for analysis.

A. Measurement Results of RSSI and SNR Values with Respect to Distance Variation

After all components of the LoRa-Based WSN system were fully integrated and functioning properly, wireless communication performance testing was conducted to evaluate the quality of data transmission between the sensor nodes and the receiving node (sink node). The testing focused on two main parameters: RSSI and SNR, which represent the strength and quality of the signal during data transmission. Each measurement was performed three times to obtain more accurate results, and the average values were taken. The tests were conducted under NLoS conditions to reflect the real implementation environment of the smart waste bank monitoring area. The average measurement results of RSSI and SNR at each distance are presented in Table III.

TABLE II
LORA COMMUNICATION PARAMETERS

Parameter	Value
Frequency	433 MHz
Spreading Factor (SF)	SF9
Bandwidth (BW)	125 kHz
Coding Rate (CR)	4/5
Transmission Power	17 dBm
Modulation	Chirp Spread Spectrum (CSS)

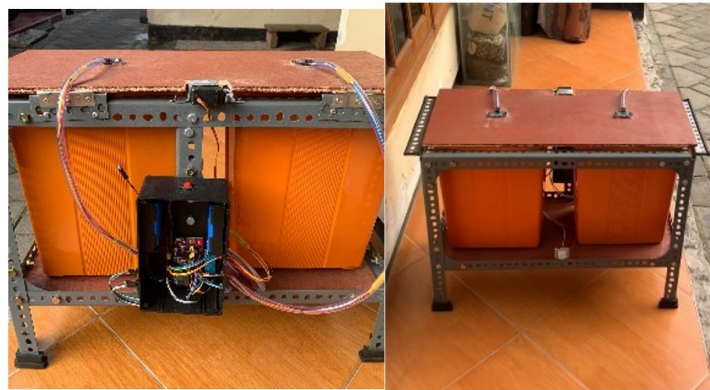


Fig. 5 Physical implementation of the smart waste bank system

TABLE III
MEASUREMENT RESULTS OF RSSI AND SNR
VALUES WITH RESPECT TO DISTANCE

Distance (m)	RSSI (dB)	SNR (dB)
10	-56	6.3
50	-92	5.8
100	-93	5.5
200	-95	4.8
300	-97	4.3
400	-99	3.8
500	-100	3.4
600	-103	2.9
700	-105	2.3
800	-108	1.9
900	-110	1.4
1000	-112	1.0

Based on Table III, the RSSI values show a clear decreasing trend as the transmission distance increases, ranging from -56 dB at 10 m to -112 dB at 1000 m. This behavior follows the log-distance path loss model, where received signal power decreases logarithmically with distance. Signal attenuation becomes more pronounced beyond 400 m, which can be attributed to non-line-of-sight conditions at the test site, including buildings, trees, and concrete structures. Despite the observed signal attenuation, the LoRa SX1278 module maintained communication up to a distance of 1 km. With a receiver sensitivity of approximately -120 dB to -123 dB, the system retained a reception margin of around 10 dB at the maximum distance, enabling stable data reception. These findings are consistent with previous studies conducted at 433 MHz, which reported similar RSSI degradation patterns under obstructed environments [21,

22]. The SNR values also exhibit a decreasing trend with increasing distance, declining from 6.3 dB at 10 m to 1.0 dB at 1000 m. This reduction reflects the increasing influence of environmental noise and interference on the received signal. Nevertheless, the SNR values remain above 0 dB across all tested distances, indicating that the signal quality is still sufficient for reliable data decoding. This result highlights the robustness of LoRa’s Chirp Spread Spectrum modulation and Forward Error Correction mechanisms, which enable operation under low-SNR conditions [23].

B. Packet Delivery Ratio (PDR) Evaluation with Respect to Distance Variation

In addition to the RSSI and SNR parameters, the communication performance of the system was also evaluated based on the PDR — the percentage of data packets successfully received. This parameter reflects the reliability of data transmission between the sensor node and the receiver node (gateway) during testing. A high PDR value indicates that the system can consistently transmit data with minimal packet loss caused by signal degradation, interference, or non-ideal environmental conditions.

The testing process involved repeatedly sending a series of data packets from the sensor node to the gateway at various distances, ranging from 10 meters to 1000 meters. The success rate was calculated as the ratio of correctly received packets to the total number of packets sent. The average PDR measurement results for each tested distance are presented in Table IV.

Based on Table IV, the PDR results demonstrate excellent communication reliability at short to medium transmission distances. At distances between 10 m and 100 m, all transmitted packets were successfully received, resulting in a PDR of 100%. As the distance increased to 200 m and 400 m, the PDR slightly decreased to 99% and 97%, respectively, indicating the

gradual impact of path loss and environmental interference. At a transmission distance of 1000 m, packet reception became highly unstable under severe non-line-of-sight conditions, leading to inconsistent packet delivery. As a result, a reliable PDR value could not be obtained and is therefore marked as unavailable in Table IV.

A more noticeable performance degradation occurs between 600 m and 800 m, where the PDR decreases from 95% to 91%. This decline corresponds closely with the observed reductions in RSSI and SNR, confirming a direct relationship between signal quality degradation and packet loss in LoRa-based communication systems operating at 433 MHz. The observed degradation in RSSI, SNR, and PDR at longer distances is strongly influenced by environmental conditions at the deployment site. The semi-urban test area includes buildings, vegetation, and other obstructions that introduce attenuation and multipath effects. Although weather conditions were not explicitly measured, the results reflect realistic challenges commonly encountered in community-scale IoT deployments.

Although this study does not propose a new communication protocol or perform comparative benchmarking with other LPWAN technologies such as NB-IoT, its contribution lies in providing empirical evidence of LoRa-based WSN performance within a practical and application-specific deployment scenario. The results demonstrate that a hybrid multi-hop and star topology can maintain reliable communication for Smart Waste Bank operations under semi-urban non-line-of-sight conditions. These findings offer practical insights for system designers and local communities seeking low-cost and infrastructure-independent IoT solutions. Although sensor accuracy was not quantitatively assessed, the ultrasonic measurements were sufficient to support system functionality and validate end-to-end data transmission in the Smart Waste Bank application.

TABLE IV
PACKET DELIVERY RATIO VALUE WITH RESPECT TO DISTANCE

Distance (m)	Packets Received (%)
10	100
100	100
200	99
400	97
600	95
800	91
1000	-

IV. CONCLUSION

Based on the implementation and testing results, the LoRa-based WSN system for the Smart Waste Bank application has demonstrated stable and reliable performance under semi-urban environmental conditions. The experimental results show that the RSSI value gradually decreases from -56 dB at a transmission distance of 10 m to -112 dB at 1000 m, following the typical log-distance path loss pattern commonly observed in wireless communication systems. Although signal strength decreases with increasing distance, the LoRa SX1278 module is able to maintain communication up to 1 km, supported by its high receiver sensitivity (around -123 dBm). The SNR value also decreases from 6.3 dB to 1.0 dB but remains within the positive range, indicating that the signal quality is sufficient for data decoding. The PDR results demonstrate excellent system reliability, achieving an average of 97% across all testing scenarios up to a distance of 800 m. These findings confirm that the proposed system can operate effectively even under environmental interference and non-line-of-sight conditions, making it suitable for community-scale IoT deployments with limited network infrastructure. Despite the promising results, this study has several limitations that should be acknowledged. The performance evaluation focuses on a single deployment scenario and does not include scalability analysis involving a larger number of sensor nodes. In addition, radio communication parameters such as spreading factor, bandwidth, and transmission power were kept fixed throughout the experiments and were not dynamically optimized. Energy consumption and node lifetime were also not quantitatively measured. These limitations indicate opportunities for further investigation. Future work will address these issues by incorporating scalability testing with denser node deployments, adaptive radio parameter tuning, and detailed energy consumption and lifetime analysis. Comparative performance evaluation with other LPWAN technologies and extended testing under diverse environmental and weather conditions are also considered important directions to enhance system robustness and applicability.

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