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LoRa-Based IoT Recommendations for Surabaya City Drainage Channel Using Multi-Node Multi-Hop Communication

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Abstract—**This paper focuses on the development of a multi-hop long-range (LoRa) communication network for real-time monitoring of urban drainage internet of things (IoT), specifically simulating the flood-prone area along the drainage channel of Jawa Street, Surabaya City. The novelty of this research lies in the selection of the optimal communication environment through path loss (PL) and shadowing analysis prior to implementing a multi-node, multi-hop, sensor medium access control (S-MAC) method. The selected environment at the first location demonstrated a lower PL exponent of 1.55, typical of "in-building line-of-sight," compared to the second location with a loss exponent of 2.82, which resembled "urban area cellular radio." Applying the multi-hop technique successfully extended the data transmission range up to 750 m with nodes placed at 250 m intervals while maintaining a high data transfer rate. The experiments showed that increasing distance significantly reduced the received signal strength indicator (RSSI), with values dropping from –52.75 dBm at 150 m to –98.25 dBm at 750 m. This paper demonstrates the feasibility of using multi-hop communication rather than the conventional multi-node technique to ensure reliable data transmission and wider range, offering a solid foundation for building a robust communication network in urban drainage monitoring systems.**

Keywords: flood mitigation, wireless sensor network, multi-hop network, sensor mac protocol, path loss model

I. Introduction

The 10th World Water Forum conference held in Nusa Dua, Bali, resulted in a commitment to strengthening water resource utilization in Indonesia. This initiative includes the development of water infrastructure, such as the expansion of 3 million hectares of irrigation networks to address flooding. Despite progress being made, several issues remain, particularly those affecting Southeast Asian countries. These include poor political policies, inadequate environmental regulations, pollution, and corruption. Such challenges exacerbate water insecurity, which has significant consequences for Indonesia. Currently, a majority of the population is exposed to contaminated water sources, and only 12% have access to clean water. This situation contributes to the rising prevalence of child stunting and hampers the economic potential projected for 2045 [1].

To address clean water acquisition, wastewater has become an integral source for recycled water, functioning alongside river water and groundwater before undergoing treatment at the Surya Sembada Water Treatment Plant (WTP) in Surabaya City. The cleanliness of drainage networks also plays a crucial role in determining the success of water purification processes. In efforts to meet non-potable water demands in the post-pandemic era, Ali et al. [2] such as uprating the existing water treatment plant (WTP proposed enhancing the production capacity of Local Government Owned Water Utilities (PDAM) facilities. Their research highlights the correlation between access to clean water and improved public health outcomes. Preventative measures are therefore essential to mitigate water supply disruptions caused by flooding and water anomalies. Thus, enhancing water management systems is a key recommendation in this project.

In managing stormwater runoff, Stec et al. [3] advocated for the optimization of existing waterway designs to improve water quality and the efficiency of bioretention systems (BRS). Retention and infiltration processes can perform optimally when peak flow events caused by flooding are effectively managed. This is especially important in reducing stormwater runoff from catchment areas, thus ensuring efficient water processing and avoiding overflow-related contamination. In testing hydrodynamic models for stormwater runoff using low impact development (LID) facilities, the efficiency of runoff reduction can be further improved through the use of monitoring devices and flood-warning systems. These components will be useful for the deployment of water pumps and sluice gates as needed for more effective flood

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management.

Communication support in internet of things (IoT) systems is essential for enabling wireless data transmission within drainage channels. Andreadis et al. [4] recommend deploying low-power IoT communication devices in remote or internet-deprived areas to establish an low-power wide area network (LPWAN) environment using long range wide area network (LoRaWAN) technology for monitoring essential environmental parameters. With LoRa devices, open-source medium access control (MAC) layers can be implemented as a protocol solution to address various data transmission scenarios. The development of IoT systems to support remote sensing applications for hydrodynamic parameters can include the use of water level sensors and water flow rate sensors [5].

This paper focuses on the development of IoT systems for existing drainage channels, emphasizing the calibration of sensors within data acquisition devices and the analysis of evaluation metrics derived from communication tests. One of the main contributions of this paper lies in the development of a communication protocol. Additionally, this paper introduces a novel approach by transitioning from a simple communication method to a multi-node, multi-hop MAC protocol for sensor nodes, thereby extending communication coverage within water channels and reducing the likelihood of data packet loss.

The limitation of this research lies in the testing, which relies on the calibration of LoRa devices to assess transmission quality parameters based on findings from previous research, while other parameters are derived from telecommunications literature. The researchers concur that data communication solutions for long and isolated water channels can be supported through the development of the proposed data communication protocol.

The remainder of this paper is structured as follows: Section 2 reviews literature from prior experiments, summarizing devices, evaluation methods, and testing parameters from various studies. Section 3 builds on the insights gained to describe the state of the art and provides a detailed semantic analysis applied in this paper. Section 4 presents test results from several communication experiments, highlighting the advantages of the proposed method for urban drainage applications. Finally, Section 5 concludes with a summary of the findings and a discussion of future directions for IoT system development and possibilities for further research.

II. Literature Review

Current conventional water treatment systems emphasize the accessibility of data monitoring for all stakeholders interested in development, whether for automation, forecasting, or other purposes. One of the key challenges in data collection, particularly in areas without internet access, lies in selecting appropriate devices and determining effective data transmission methods. This paper reviewed various previous studies to identify trends in IoT system development for aquatic environments. This review enabled us to determine suitable radio frequency modules, optimal data transmission techniques, and evaluation metrics to validate the success of the proposed transmission method.

Table 1. IoT devices trend for water management and monitoring system

Sensors		Communications	Sites
CO_2	Pressure	2G	Aqua tanks
Corrosion	Proximity	3G	Crab pond
DO	Pulse	Ethernet	Drain channel
Electrical conductivity	Rain	GPRS	Fish farms
	Salinity	GSM	Fishpond
Flow	Soil humidity	LoRa	Lake
Humidity	TDS	LoRaWAN	River
Laser	Temperature	RFID	Rural areas
Leakage	Turbidity	NB-IoT	Wastewater
Moisture	Ultrasonic	Wi-Fi	Water pump station
ORP	Vibration	Wi-Fi to cloud	
pH	Water level	ZigBee	Water station

The component selection recommendations are based on a systematic review by Ismail et al. [6], which explored the latest technologies in IoT applications for water management, including diverse sensors and data communication devices. Furthermore, a systematic review by Zulkifli et al. [7] provided insights into current trends in sensing techniques, sensor integration, wireless data acquisition mechanisms, and automation control systems. The range of sensors and communication devices reviewed is detailed in Table 1.

For IoT communication system design, this research selected LoRa technology due to its suitability for remote operations, as well as its advantages in power efficiency and extended range compared to wireless fidelity (Wi-Fi), narrowband IoT (NB-IoT), and ZigBee. Regarding sensor selection, given this paper's focus on water flow optimization and flood handling systems, the researchers chose ultrasonic sensors and water flow rate sensors.

The development of LoRaWAN architecture has been the focus of numerous studies, each proposing their own novel enhancements. Simple LoRa protocol implementations are still widely applied across various use cases. Studies utilizing a single node as a transmitter, directly communicating with a gateway receiver, are prevalent for private and localized data processing needs, such as transmitting patient data to doctors [8] or identifying a specific plant sample for laboratory analysis [9]. Multi-node implementations, however, require careful timing adjustments to avoid data collisions. Such research often aims to compare data collection across multiple locations, such as solar panel power estimation [10] or waste management monitoring [11].

Further focus has been placed on improving LoRaWAN architecture by modifying communication protocols to enhance data transmission quality. Prasetyo et al. [12] proposed integrating multiple low-power, long-range communication devices within an LPWAN network using LoRa technology. Their proposed LoRa multi-communication (LMC) algorithm leverages MAC principles, which extend time on air (TOA) but improve

Table 2. Research summary conducted in Multi Nodes Communication

Reference	LoRa module	Metrics	Parameters
[11]	RFM95	RSSI, PDR	Humidity, distance, location
[12]	HopeRF95	PRR, TOA	Address, payload, status, temperature, humidity, current
[13]	E32-433T	PDR, RTT	Location, payload, power, CR
[14]	RFM95	PRR, RTT	Address, time
This Paper	E220-900T	RSSI, PL	water level, water flow rate, rain status, RSSI Method

packet reception ratio (PRR) and battery life time due to the implementation of sleep mode during idle times. Liang et al. [13] also explored data transmission with a similar packet structure in indoor environmental applications. Their evaluations revealed that increasing payload length (PL) and transmission distance led to higher round-trip time (RTT) and reduced packet delivery rate (PDR).

LPWAN design incorporating multi-hop communication aims to extend range and circumvent obstacles in data transmission. Triwidyastuti et al. [14] utilized relay nodes to transmit data from sources to final destinations. Although adding relays increases payload length and impacts RTT, employing appropriate protocols ensures a consistent PRR. In this research, sensors can also serve as relay nodes. This research novelty focused on adopting the routing protocol proposed by Agussalim et al. [15] to implement multi-hop communication within a wireless mesh network using LoRa technology. Additionally, this paper added the environment selection technique for optimized multi-hop communication simulations using path loss (PL) and shadowing analysis.

Table 2 outlines the types of LoRa modules, reliability metrics based on evaluations, and data transmission parameters used in prior research. The reliability metrics selected for this research include received signal strength indicator (RSSI) and PL. First, the RSSI provides a measure of signal strength at the receiver, while lower RSSI values indicate poor transmission quality and an increased probability of data packet delivery losses. Second, PL measures the effectiveness of data transmission by calculating the parameters that impact the received packet's data quality. These metrics are particularly relevant for LoRa applications, specifically with the E220-900T module, as its handshaking mechanism minimizes low-quality data communication and reduces the risk of high packet loss due to environmental factors. This evaluation excludes considerations of TOA or RTT, as these introduce additional complexity to measurements due to the LoRa module limitation and fixed data transmission intervals from the default MAC protocol.

A. Proposed System Design

The design of this system encompasses a comprehensive water treatment system aimed at providing flood warning notifications and enabling big data acquisition from water channels for further research development. The proposed IoT architecture is outlined sequentially as depicted in Figure 1. First, urban drainage systems, which address stormwater runoff from buildings and roads directed into water channels, serve as the primary issue the researchers aim to resolve. Second, water quality data critical for flood warnings typically involve water level measurements, thus the researchers incorporate water flow parameters as an additional benchmark to evaluate the impact of stormwater runoff before it reaches water treatment facilities or pumping stations. Third, daily large-scale data has been utilized for forecasting hydrodynamic parameters in the researcher previous studies using long short-term memory (LSTM) and gated recurrent unit (GRU) techniques [16]. However, for this research, the experiments require more localized water data based on specific data collection sites.

Fourth, monitoring is facilitated through IoT cloud services using the ThingSpeak server, which displays real-time measurement data or computational results [17]. Forecasted data can serve as a reference for preventive

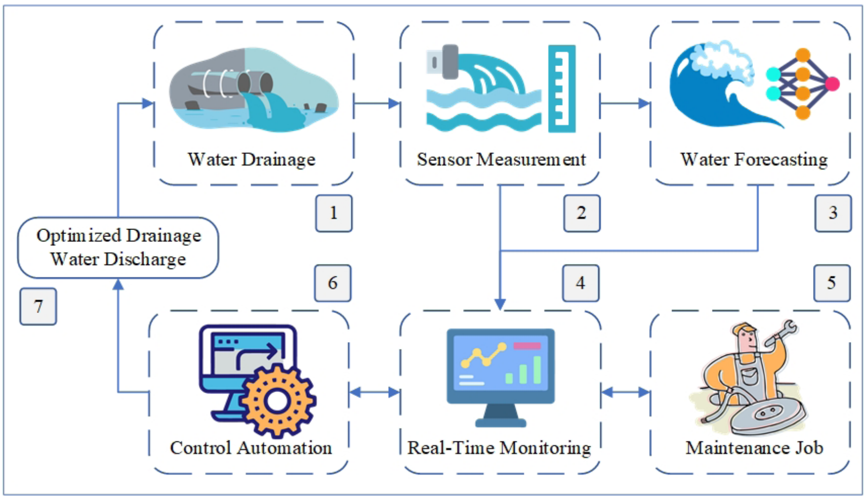


Figure 1. The system architecture of the research's proposed solution

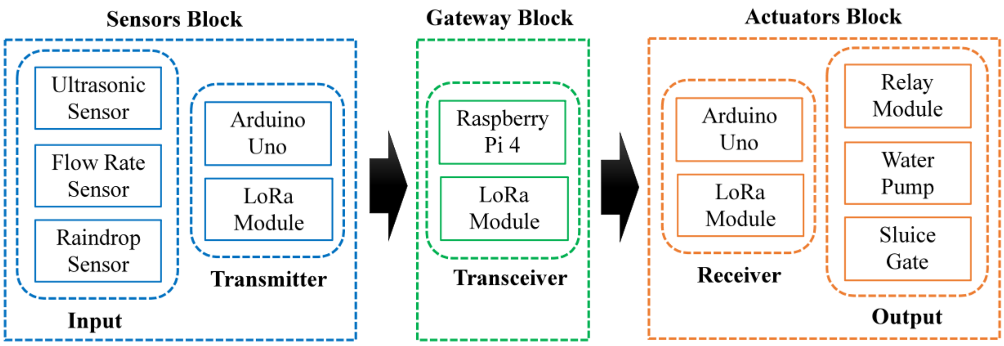


Figure 2. Sensors and actuators selections of the research's hardware design

solutions, such as issuing warnings before flooding occurs, while real-time measurement data is essential for corrective measures addressing extreme rainfall events that exceed system predictions. This solution can be implemented through alerts sent to maintenance staff and operators to coordinate responses to problematic water channels in step five [18]. The sixth step involves recommendations for future research on automation applications, resulting in the optimized drainage water flow and smoother water discharge in step seven.

B. Hardware System Design

The hardware design proposed in this paper is aimed at establishing a water management system with an emphasis on improving data communication quality. Accordingly, the have divided the functions of the nodes into three categories: sensor nodes, which act as transmitters; gateway nodes, which function as transceivers; and actuator nodes, which serve as receivers. Each node, as illustrated in Figure 2, is equipped with the LoRa Ebyte E220-900T22D module operating at a frequency of 915 MHz.

The communication module selected for this system is the Ebyte E220-900T, which operates at a frequency of 915 MHz with a transmission power of +22 dBm. Although this module is capable of achieving a communication range of up to 5 km under ideal conditions, in practical applications, physical obstructions in urban environments significantly impact communication reliability. In accordance with the device specifications, testing can be conducted within a frequency band ranging from 850.125 to 930.125 MHz. The module also features high receiving sensitivity, reaching up to −147 dBm. However, with an air data rate of 2.4 kbps, it is best suited for fixed environment applications [19]. Therefore, the module's specifications are deemed appropriate for the experimental conditions in

Figure 3. Drainage channel length for sensor node placements

this research.

The selection of sensors in the input block is based on a performance comparison of sensors for aquatic environments in previous studies [20]. The sensors used include the HC-SR04 ultrasonic sensor for water level detection, and YF-B10 sensor for measuring water flow rate by utilizing the height and width of runoff in an open channel, as well as the MH-RD rain sensor for rainfall detection. Data acquisition is processed using an Arduino Uno microcontroller before being transmitted to a Raspberry Pi 4 microprocessor for data processing and evaluation.

C. Communication System Design and Development

The communication design is focused on implementing communication methods to extend the communication range within the developed hardware system configuration. This design considers the limitations of data transmission range using LoRa technology for inter-node communication [21]. Based on the study case located in the drainage network of Jalan Jawa, Surabaya, the length of the drainage channel for proposed communication network is shown in Figure 3.

In this case, data transmission along a 700 m water channel cannot be achieved with a single sensor node. Additional sensor nodes are required along the water channel to study the characteristics of water at different points and to serve as relay nodes between other nodes [22]. In the experiment conducted in a densely populated area, the optimal communication range of LoRa was limited to 200 to 300 m, necessitating at least three relay sensor nodes to cover the 700 m distance. The architecture of the communication network between nodes is depicted in Figure 4.

This method is adapted to LoRa technology, which operates in a star topology network, requiring specific configurations to implement multi-hop communication in a multi-node setup. Furthermore, the designed system generates different data formats at each node. The sequential steps outlined in Table 3 indicate the node sending data and its destination. Each data format includes information such as water level, flow rate, rain status, and RSSI. With each transmission step, an additional data format from the preceding node is included, increasing the

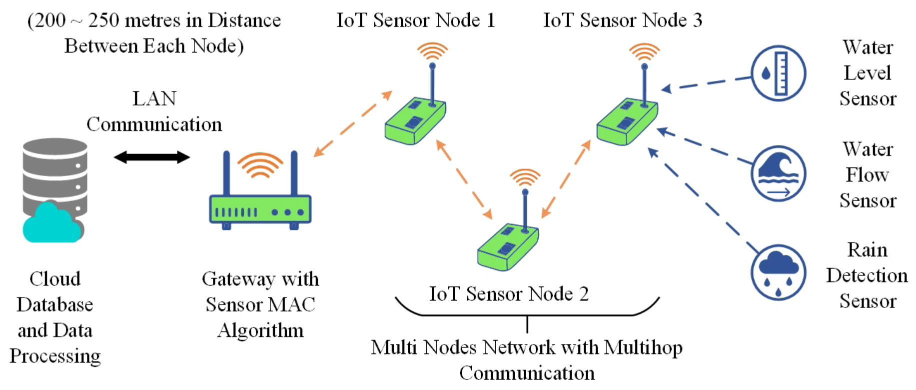


Figure 4. Multi-sensor multi-hop implementation of the proposed solution

Table 3. Data format allocation for different data transmission tasks

Sequential step	Sending node	Receiving node	Data format
1	Sensor_3	Sensor_2	X
2	Sensor_2	Sensor_1	X + Y
3	Sensor_1	Gateway	X + Y + Z

payload length [23].

For effective routing in the communication network, a scheduling technique that encompasses all connected nodes is required. The researchers designed a sleep scheduling system to allocate time intervals for data collection from the first sensor node to the second sensor node before finally being delivered to the gateway node using the same following pattern as detailed in Table 4 [24].

With the LoRa module used in this experiment, the handshaking process requires up to 5 s for each data exchange. Each node is assigned an address for ease of identification, particularly for implementing the sensor MAC protocol, which requires timing adjustments to optimize power consumption for each node. According to the designed scheduling system, the maximum number of sensor nodes that can be accommodated within a minute using the same LoRa module is four [25].

Table 4. Timing configuration of data transmissions in sequential order

Nodes	Time				
	2.5 s	0.5 s	5 s	0.5 s	5 s
Sensor_3 Address: 2342	Sensing	Delay	Send ‘2342’	Delay	Send “Sensor3data”
Sensor_2 Address: 2242	Sleep	Delay	Receive ‘2342’	Delay	Receive “Sensor3data”
Sensor_1 Address: 2142	Sleep	Delay	Receive ‘2342’	Sleep	Sleep
Gateway Address: 2042	Sleep	Delay	Receive: ‘2342’	Sleep	Sleep

To facilitate the understanding of data format allocation and timing configuration for each node, Figure 5 illustrates the proposed flowchart of the multi-node, multi-hop LoRa communication system. Each node is assigned a unique

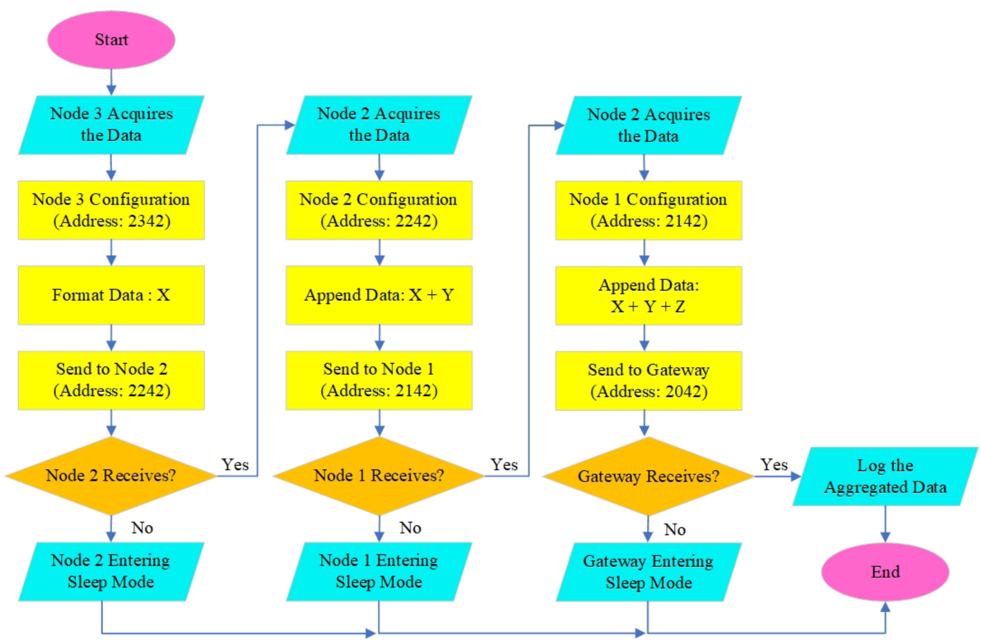


Figure 5. Flowchart of the multi-node multi-hop communication protocol

address to enable coordinated communication and proper handshaking. This also implies that each node's LoRa module is configured individually.

The researchers recognize that continuous data transmission or idling are the most power-consuming aspects, making them unsuitable for IoT architecture implementation. Therefore, to optimize energy efficiency and ensure synchronized transmission, this system adopts scheduled sleep cycles. If a node fails to receive the expected data within its time slot, the node does not attempt retransmission but instead enters sleep mode until the next scheduled start condition. This mechanism reduces unnecessary energy consumption and ensures an orderly communication flow without packet collisions.

D. PL Modelling and Area Identification

In determining PL for further analysis, this research applies a basic equation using received and transmitted power along with the gain on both sides. A more detailed analysis method using PL at reference distance $PL(d_0)$ can be conducted as follows [26]:

$$PL(d_0) = P_{TX} + G_{TX} + G_{RX} - P_{RX}(d_0), \quad (1)$$

where P_{TX} and G_{TX} are the transmitter's power and gain in dBm, while P_{RX} and G_{RX} represent the received power and gain in dBm at the specified reference distance d_0. In this paper, the reference distance d_0 was set at 50 m intervals, with the transmission power fixed at 22 dBm.

To create prediction curves, it is common to use the log-distance PL model $PL(d)$ which utilizes d as the distance between the transmitter and receiver, as expressed in [27]:

$$PL(d) = PL(d_0) + 10n \times \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad (2)$$

where X_σ is a zero-mean Gaussian random variable with a standard deviation. Although it is not explicitly displayed in the model, X_σ can represent shadowing or gain variations in PL data.

This paper's analysis aimed to classify the obtained PL data based on the PL exponent [28] and standard deviation values [29] in different environments. The suitability of a location will later be determined by comparing the PL and standard deviation values obtained with those corresponding to the classified environments shown in Table 5.

Furthermore, this model incorporates a logarithmic function of the distance ratio d/d_0, scaled by the PL exponent n, which facilitates the characterization of signal degradation as a function of distance. By incorporating the stochastic component X_σ, the model enables dynamic simulation of noise fluctuations, such as those caused by shadowing or environmental variability. The inclusion of this equation allows for comprehensive evaluation and prediction of signal attenuation behavior across various environments, providing valuable insight for the configuration and optimization of wireless communication systems on hardware platforms, which can be beneficial for future analytical applications.

Table 5. Classification of PL exponent and standard deviation (Std) value (in dB) in various communication environments

Environment	PL exponent	Environment	Std (dB)
Free space	2	Urban/suburban macrocell	8
Urban area cellular radio	2.7 to 3.5	Urban microcell	3 to 4
Shadowed urban cellular radio	3 to 5	Indoor small office	4 to 8
In building line-of-site	1.6 to 1.8	Indoor hot spot	1.1 to 1.5
Obstructed in building	4 to 6	Outdoor to indoor	7
Obstructed in factories	2 to 3	Open rural macrocell	6 to 8

III. Results and Discussion

A. Experimental LoRa Transmission Simulation

To provide recommendations for water monitoring in urban areas, the researchers aimed to select test locations that closely match the communication parameter criteria of the target area. In the first experiment, the data transmission in an urban setting has been tested by placing the receiver on top of a building to simulate non-line-of-sight (NLoS) propagation. The configuration of the LoRa E220 module, as shown in Figure 6, was necessary to enable RSSI measurements.

This research method involved analyzing data transmission quality by sending dummy data that represents drainage water parameters. The data packet structure in each transmission influenced the different payload sizes, which will be evaluated in the next subsection. Figure 7 shows the testing devices arranged according to their roles in the communication network.

In the first experiment, single-node communication

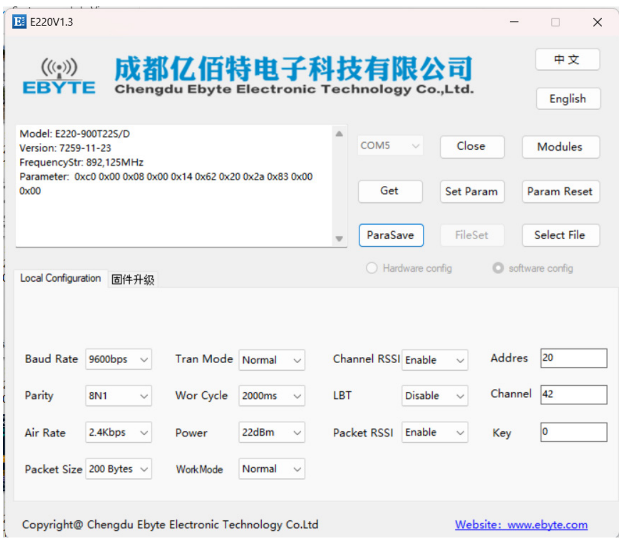


Figure 6. Ebyte E220-900T22D LoRa module configuration

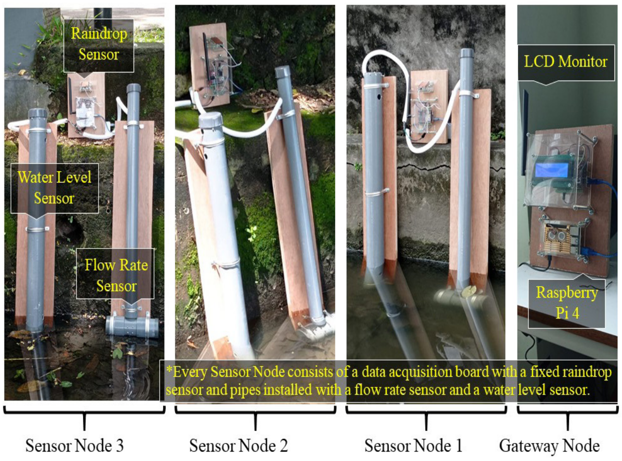
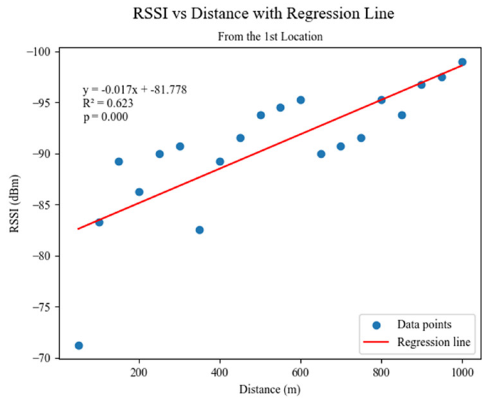


Figure 7. Designed sensor devices and data acquisition boards

was performed from sensor node 1 (transmitter) to the gateway node (receiver). In the next experiment, multi-node communication will utilize all nodes (sensor node 3, 2, 1, and the gateway node). The first data collection projection was conducted at Raya ITS str., Surabaya, while the second data collection projection took place at Bendul Merisi str., Surabaya, as shown in Figure 8.

At the first location, the data transmission range reached up to 1 km, while the second location had different characteristics depending on the direction. In the eastward projection, the propagation distance was limited to 300 m due to the presence of numerous obstacles, which caused a decline in data transmission quality. To justify the choice of these locations for simulating similar urban areas, the experiment measured RSSI at multiple points, with the reported RSSI being the average of 10 measurements. A linear regression analysis was conducted to observe the relationship between RSSI and distance at different locations. The evaluation metrics for the linear regression model are shown in Figure 9.

From the analysis of RSSI versus distance, it was observed that the second location had a steeper slope of –0.080 compared to the first location with a slope of –0.017. This indicates that the signal at the second location weakened more rapidly with distance due to more obstacles and higher signal attenuation. The R-squared (R^2) evaluation indicated the accuracy of the regression



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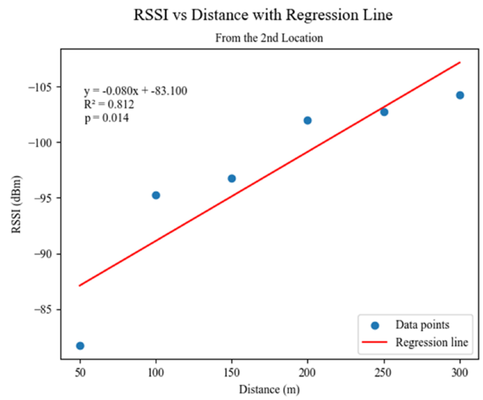
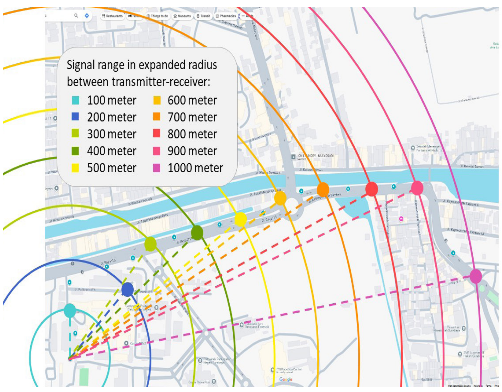


(b)

Figure 9. RSSI vs distance plotting with linear regression line at: (a) first location; and (b) second location

line in representing the actual measurement variability. In this case, the second location had a better R^2 value of 0.812 compared to 0.623 at the first location. The main contributing factor was that measurements at 50 ms consistently showed significantly higher RSSI values.

The p-value evaluation demonstrated the significance of the correlation between RSSI and distance. At the first location, the p-value was extremely low at 0.000 or 3.494e-5, while at the second location, it was 0.014. Both p-values indicated a strong correlation since they were below 0.05, confirming the validity of the relationship between RSSI and distance in both cases. However, it is worth noting that the first location had stronger certainty due to the minimal presence of obstacles [30].



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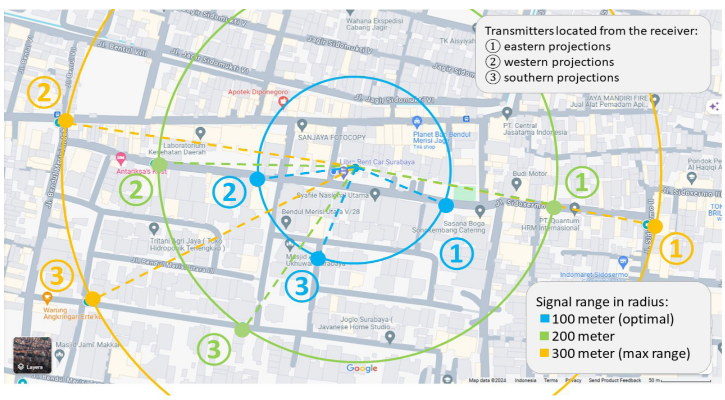
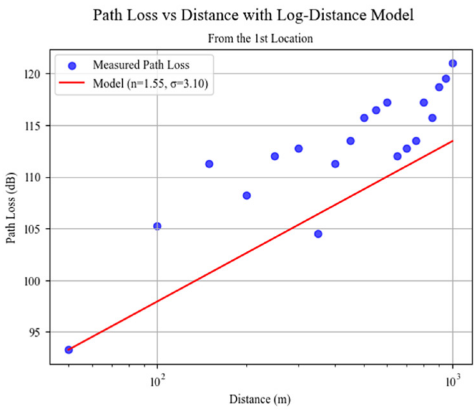


(b)

Figure 8. Transmitter placements projection for the single-node experiment at: (a) first location; and (b) second location



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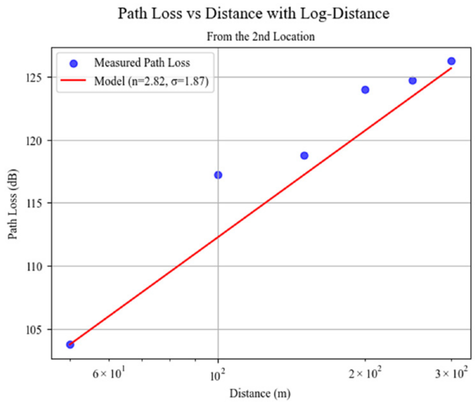
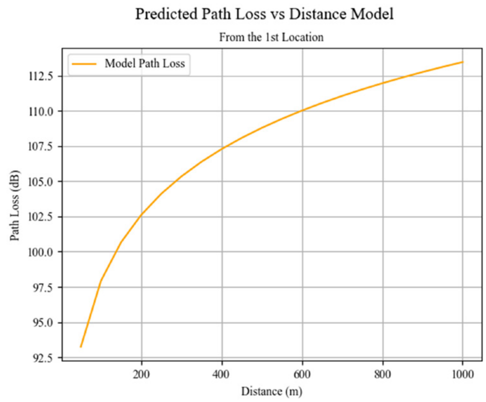


(b)

Figure 10. PL plotting using the log-distance model at: (a) first location; and (b) second location



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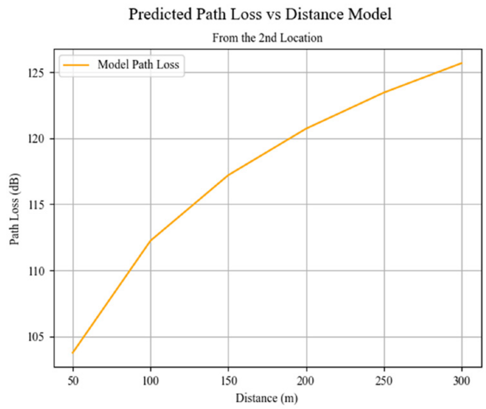


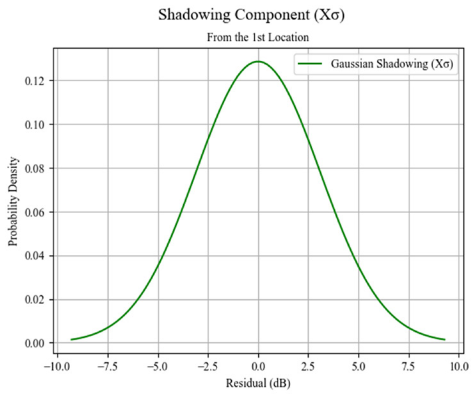
(b)

Figure 11. PL curve plotting based on distance equation at: (a) first location; and (b) second location

B. *Predicted Model PL Analysis*

The obtained RSSI values assumed to represent received power at a given reference distance, can assist researchers in constructing a PL model. The suitability of each location was determined by comparing the plotted results in Figure 10, which shows the PL model tested against log-distance, resulting in the PL exponent and standard deviation for each location. The PL modelling analysis at the first location resulted in better signal propagation, with a lower PL exponent of 1.55 compared to 2.82 at the second location. This indicates that the increase in PL at the first location is slower relative to distance. The value at the first location closely aligns with the “in-building line-of-sight” range, whereas the value at the second location falls within the “urban area cellular radio” range (2.7 to 3.5). The PL curve plotted against distance without shadowing is shown in Figure 11, while the standard deviation for shadowing, which represents the residual gain (in dB), is shown in Figure 12 [31].

In the standard deviation shadowing analysis, the first location exhibited higher standard deviation fluctuation at 3.10 dB compared to 1.87 dB at the second location, likely due to a broader data range and environmental changes. Both locations’ values are closest to “urban microcell” conditions. However, the second location demonstrates more uniform attenuation, likely due to its smaller range. The propagation characteristics at the second location,



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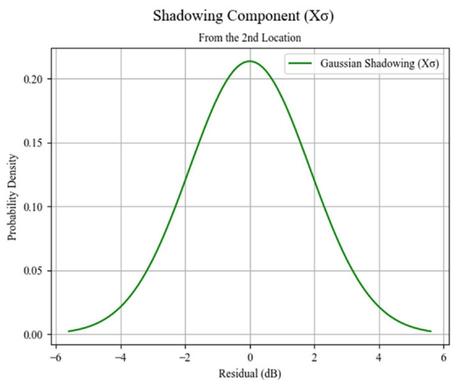

(b)

Figure 12. Standard deviation curve plotting for shadowing gain at: (a) first location; and (b) second location

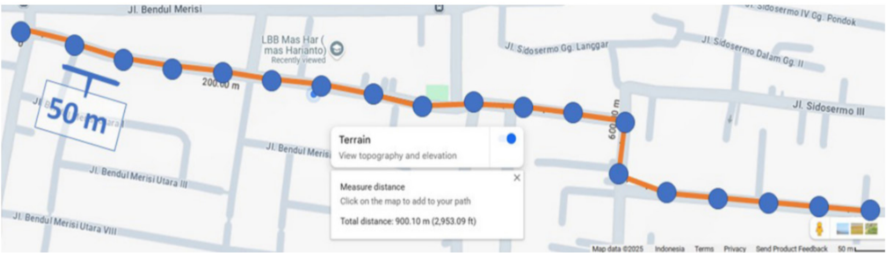

Figure 13. Expanded node projection mapping based on the second location

with a more accurate PL exponent for urban areas, suggest that it is more suitable for further simulation applications [32].

A. Multi-Node Multi-Hop LoRa Application

Based on the previous subsection's tests, the second location is suitable for further simulation due to the urgency of urban area conditions. The issue of significant attenuation can be resolved by installing relay nodes that also function as sensor nodes for data acquisition and sequential data transmission. Figure 13 illustrates an expanded projection of node placement in this area to determine the extent to which this method can be successful.

This test is accompanied by a comparison of RSSI results against distance and payload in Bytes. The payload calculation used in the multi-hop test is shown on the serial monitor in Figure 14. The data propagation method is divided into hop counts that represents sequential data transmission roles, as follows:

1. Hop count 1: from sensor node 3 to sensor node 2;
2. Hop count 2: from sensor node 2 to sensor node 1;
3. Hop count 3: from sensor node 1 to gateway node.

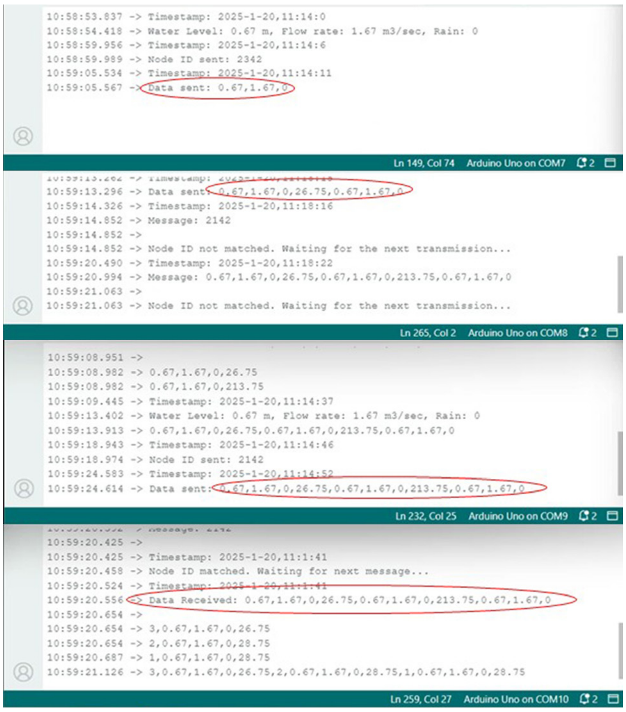

Figure 14. Serial monitor display for sequential multi-hop algorithm

The testing conducted via the serial monitor in the Arduino IDE confirmed that the data send and data receive commands were successfully executed in sequence up to the final node. This evaluation implies the system's operational reliability, thereby justifying the continuation to real-world measurement in subsequent experiments. In this experiment, the RSSI measurement results based on distance and payload are summarized in Tables 6 to 10. The total distance starts from 150 m (with 50 m intervals between nodes) and continues up to 750 m.

Through the average 10 tests at each point, this experiment found a consistent correlation indicating that distance is the dominant factor in RSSI degradation. In the first test, the average RSSI for different payload values at the same distance was –52.75 dBm. This decreased to –59.75 dBm in the second test, –78.25 dBm in the third,

Table 6. LoRa multi-hop communication test results for 150 m (50 m between nodes)

Hop count	Payload (Bytes)	Distance (m)	RSSI (dBm)
1	11	50	–54.75
2	30	50	–52.5
3	49	50	–51

Table 7. LoRa multi-hop communication test results for 300 m (100 m between nodes)

Hop count	Payload (Bytes)	Distance (m)	RSSI (dBm)
1	11	100	–58.5
2	30	100	–57.75
3	49	100	–63

Table 8. LoRa multi-hop communication test results for 450 m (150 m between nodes)

Hop count	Payload (Bytes)	Distance (m)	RSSI (dBm)
1	11	150	–78.75
2	30	150	–83.25
3	49	150	–72.75

Table 9. LoRa multi-hop communication test results for 600 m (200 m between nodes)

Hop count	Payload (Bytes)	Distance (m)	RSSI (dBm)
1	11	200	–89.25
2	30	200	–97.5
3	49	200	–95.25

Table 10. LoRa multi-hop communication test results for 750 m (250 m between nodes)

Hop count	Payload (Bytes)	Distance (m)	RSSI (dBm)
1	11	250	–96.75
2	30	250	–99.75
3	49	250	–98.25

–94 dBm in the fourth, and –98.25 dBm in the fifth test. This decline in RSSI with increasing distance aligns with the predicted PL model and confirms the worsening attenuation effect.

The hypothesis suggesting that payload size influences transmission delay or time-on-air, which is considered as a noise factor affecting RSSI degradation, could not be fully validated in this experiment. The RSSI test results were not consistent for the similar payload value, and the assumption that increasing payload size leads to a drop in RSSI was not entirely proven in some locations due to the complex urban environment. The correlation between RSSI reduction and increased payload size was observed only in the second, fourth, and fifth tests. In these tests, for the 49 Byte payload, the obtained RSSI values were –63 dBm, –95.25 dBm, and –98.25 dBm, which were lower compared to the 11 Byte payload at –58.5 dBm, –89.25 dBm, and –96.75 dBm, respectively.

The limitations of this experiment are reflected in the first and third tests, where a decrease in RSSI was not observed. The inconsistency in the impact of payload size on RSSI is likely attributed to environmental factors such as multipath fading, where reflected signals interfere with the direct signal path, or the presence of other radio frequency (RF) sources in the same environment. Moreover, in further testing, using higher payload rates approaching the maximum transmission unit (MTU) tended to result in data collisions and interference, necessitating reconfiguration to maintain program functionality.

Additionally, the data communication tests showed a high percentage of successful data transmission every minute within a range of less than 250 m between nodes, rendering PDR or PRR analysis less impactful. Another significant finding was identifying the maximum achievable communication distance for this LoRa module in this environment. Using multi-sensor multi-hop techniques, the test experiments successfully extended the communication range to 750 m with 250 m intervals between nodes.

C. *LoRa Based Recommendation for Drainage Channel*

This paper's recommendation is supposed to create a communication network along the drainage canal on Jawa str., Surabaya. Therefore, a modified site plan for node placement is shown in Figure 15. The drainage authority has identified road intersections as potential bottleneck points during water overflow. Hence, the detailed node placement is as follows:

1. Sensor node 3 (200 m): Positioned to detect water parameter after the intersection of Nias str.;
2. Sensor node 2 (200 m): Placed after the Bliton str. intersection, which is also prone to flooding;
3. Sensor node 1 (250 m): The last sensor node located after the intersection of Raya Gubeng str.;
4. Gateway node: Positioned at Karimun Jawa Pump House.

Water overflow in the drainage network can be mitigated by installing water pumps or floodgates near the sensor nodes to provide real-time solutions. Researchers can also send actuator commands if the sensors detect water level or flow rate values that exceed the threshold and indicate potential flooding. Additionally, optimizing communication quality can be achieved by increasing the LoRa module's transmission power, adding more nodes, and placing the antenna at a higher elevation to avoid signal attenuation caused by obstacles or ground interference.

However, it should be noted that there are limitations in terms of scalability when applying this method to more complex networks. This recommendation is intended for achieving a low-power system, and therefore it may not be optimal for streaming data transmission such as RF module-based communication, due to the long handshaking time and specific sleep scheduling used for data collection at one-minute intervals. As explained in the time scheduling technique applied in the experiment, the optimal limit of LoRa devices that can be added as sensor nodes or transmitting nodes for sequential data transmission is four. In this research, three devices were used, which was sufficient to cover the desired distance and testing points along the local drainage water channel.

IV. Conclusion

This research successfully evaluated the performance of a multi-hop LoRa network in an urban environment, focusing on the correlation between distance, payload size, and RSSI. By implementing log-distance PL model, this research demonstrated the effectiveness of multi-hop

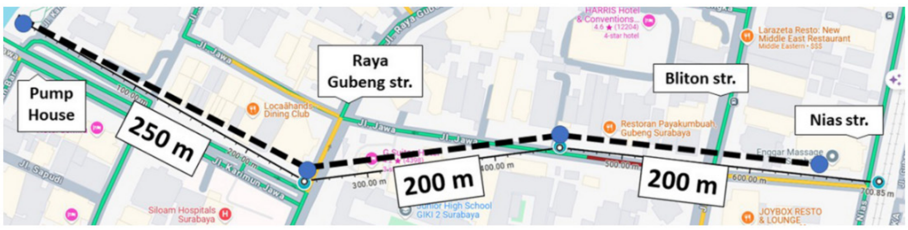

Figure 15. Recommended node placement for multi-hop data communication network in the drainage channel on Jawa str., Surabaya

communication in extending the communication range up to 750 m, with nodes placed at 250 m intervals. Environment selection using linear regression and PL analysis identified the first location as having PL exponent of 1.55, typical of "in-building line-of-sight," while the second location had a higher exponent of 2.82, similar to "urban area cellular radio." The shadowing analysis further the reasoning for location selection, with higher standard deviation of 3.10 dB at the first location, indicating more significant signal fluctuations compared to the second location with the value of 1.87 dB.

The multi-nodes multi-hop method also showing the correlation between RSSI and distance, where increasing distance significantly reduced RSSI values. For example, the average RSSI dropped from –52.75 dBm at 150 m to –98.25 dBm at 750 m. Although the effect of payload size on RSSI was not consistent across all locations, several tests showed that larger payloads (49 Bytes) resulted in lower RSSI compared to smaller payloads (11 Bytes). The analysis highlights the feasibility of using multi-hop communication for real-time monitoring in urban drainage systems, ensuring reliable data transmission. Overall, the multi-hop transmission maintained reliable communication up to 250 m between nodes with minimal data loss.

In recommendations for future research, the researchers aim to expand the computational results of the obtained dataset from the system hardware and build the decision-making rules that will be transmitted to the output for optimizing water flow rates. This includes operations such as controlling water pumps [33] or sluice gates [34], supported by IoT-enabled relay devices and motor controllers.

Furthermore, system development recommendations for future research are proposed to address the limitations identified in this paper. The researchers strongly encourage the exploration of MAC-layer protocols capable of supporting broader data allocation across larger networks. Such protocols could also be enhanced by integrating more robust communication modules to reduce latency and mitigate power trade-offs. Lastly, embedded systems equipped with the ability to execute predictive models using machine learning are highly recommended to enable more adaptive communication scheduling [35].

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