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Adaptive Control System Design Based On Lora SX1278 For Wireless Sensor Network Monitoring

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ABSTRACT
Wireless sensor network-based monitoring systems have become essential for various industrial and environmental applications, particularly for monitoring conditions requiring wide coverage and low power consumption. LoRa SX1278 technology offers a long-range communication solution with high energy efficiency, but challenges remain regarding data stability, channel interference, and the need to adapt to changing environmental conditions. This study presents the design of a LoRa SX1278-based adaptive control system for wireless sensor network monitoring, focusing on improving transmission reliability and adaptive response to signal dynamics. This system integrates a LoRa SX1278 module, a microcontroller as the main controller, and an adaptive control algorithm that adjusts communication parameters in real time based on channel conditions. Tests were conducted using several distance scenarios and physical obstacles to evaluate system performance in terms of delay, packet loss, and signal stability. The test results show that the implementation of adaptive control can improve communication quality by more than 20% compared to static methods, while ensuring continuity of monitoring data under changing environmental conditions. The main contribution of this study lies in the integration of the adaptive algorithm with the LoRa SX1278 module, which can be used as a reference in the development of large-scale IoT systems in the future.

Keywords: Internet of Things, Wireless Sensor Networks, LoRa SX1278, Adaptive Control Systems

INTRODUCTION

The development of the Internet of Things (IoT) has increased the need for reliable and energy-efficient remote monitoring systems in various fields, such as environmental monitoring, precision agriculture, and critical infrastructure. Wireless sensor networks (WSNs) have become the primary solution for collecting distributed data through sensor nodes spread across large areas (Akyildiz et al., 2020). In the field, WSN operations often face challenges such as limited node energy, fluctuations in communication channel quality, and the need for long-range, yet energy-efficient, coverage (Silva et al., 2023). LoRa (Long Range) technology has become a widely adopted platform for WSNs because it can provide communication ranges of up to several kilometers with minimal power consumption (Semtech, 2018). The LoRa-based SX1278 transceiver module offers high sensitivity, energy efficiency, and sub-GHz frequency support, making it suitable for large areas and open environments (Semtech, 2018). Recent studies have shown that LoRa-based monitoring systems are effective for environmental monitoring, air quality monitoring, and structural condition monitoring due to their ability to maintain transmission reliability over long distances (Ragnoli et al., 2023).

However, communication performance in LoRa is directly affected by network conditions, such as interference levels, changes in RSSI and SNR, and variations in data traffic load (Silva et al., 2023). In the context of remote control systems, communication disruptions can negatively impact control performance, increasing delays and triggering packet loss, which results in a decrease in service quality (Butt et al., 2025). Therefore, an adaptive mechanism is

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needed to dynamically adjust communication and control parameters according to network conditions to maintain stable system performance and energy efficiency (Jon, 2016). Most studies focus on either the communication or control aspects separately, whereas integrating the two has the potential to improve system stability, reduce energy consumption, and extend the operational lifespan of sensor nodes (Ragnoli et al., 2023).

Based on this gap, this study aims to design and implement a LoRa SX1278-based adaptive control system for wireless sensor network monitoring. The designed system will utilize real-time communication metrics (RSSI, SNR, and packet loss) as a reference to dynamically adjust control parameters and transmission strategies, thereby maintaining monitoring quality and energy efficiency in sensor networks under changing environmental conditions (Silva et al., 2023). With this design, this study is expected to contribute to the development of a LoRa-based adaptive monitoring system that is more robust, efficient, and ready for application in field scenarios.

LITERATURE REVIEW

Wireless Sensor Network (WSN)

A Wireless Sensor Network (WSN) is a network consisting of multiple sensor nodes that independently perform sensing, data processing, and wireless transmission. Nodes in WSNs generally have limited energy, range, and computational resources, necessitating efficient communication protocols (Akyildiz et al., 2020).
In general, the WSN architecture is described as follows:

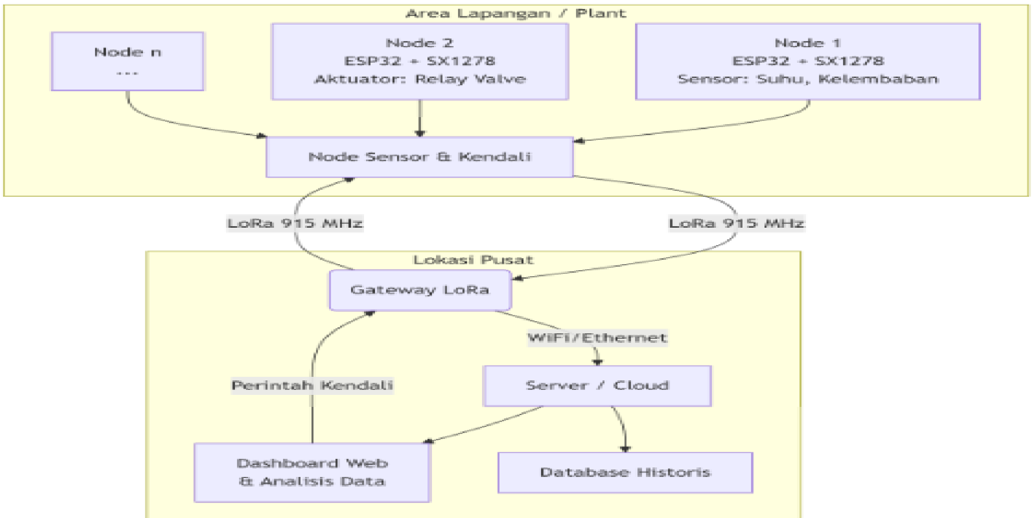

Figure 1. Wireless sensor network architecture

WSNs depend on link quality, which is influenced by RSSI, SNR, and distance. The ideal relationship between received power (Pr) and transmitted power (Pt) is modeled by the propagation equation:

$$P_r = P_t - PL(d) \quad .....(1)$$

where the path loss (PL) follows the log-distance model (Rappaport, 2016):

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$$PL(d) = PL(d_0) + 10n\log_{10}(\frac{d}{d_0}) + X_\sigma \quad .....(2)$$

with:

- n= path-loss exponent (2–4)
- X_σ= shadowing variable
- d_0= reference distance

LoRa Technology and SX1278 Module

LoRa (Long Range) is a chirp spread spectrum modulation technology that offers long range and low power consumption (Semtech, 2018). The SX1278 module operates at 410–525 MHz with a sensitivity of up to –148 dBm and a link budget of up to 168 dB (Semtech, 2018).

Figure 2. LoRa SX 1278 Module

The most important parameter in LoRa is the Spreading Factor (SF), which determines the number of chips per symbol. The relationship is:

$$R_s = \frac{BW}{2^{SF}} \quad .....(3)$$

The larger the SF → the more robust → but the data rate decreases. ToA is very important for evaluating bandwidth and energy consumption. The general formula for ToA is (Augustin et al., 2016):

$$T_{packet} = T_{preamble} + T_{payload} \quad .....(4)$$

Symbol time:

$$T_{sym} = \frac{2^{SF}}{BW} \quad .....(5)$$

The bigger → the longer the transmission → the power consumption increases.T_{sym}

Adaptive Control

*Adaptive Control*is a control strategy in which control parameters are updated automatically following system dynamics or environmental conditions (Åström & Wittenmark, 2013).

The dynamic model of a linear system is depicted:

$$\dot{x}(t) = A(\theta)x(t) + B(\theta)u(t) \quad .....(6)$$

Parameterθ can vary and must be estimated by an adaptation mechanism. One common parameter adaptation method is Model Reference Adaptive Control (MRAC).

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Equation of error tracking in MRAC:

$$e(t) = x(t) - x_m(t) \quad .....(7)$$

Adaptation laws generally use:

$$\dot{\hat{\theta}} = -\gamma x(t)e(t) \quad .....(8)$$

with

- γ= adaptation gain,
- $\hat{\theta}$= parameter estimation.

Illustration of the MRAC concept:

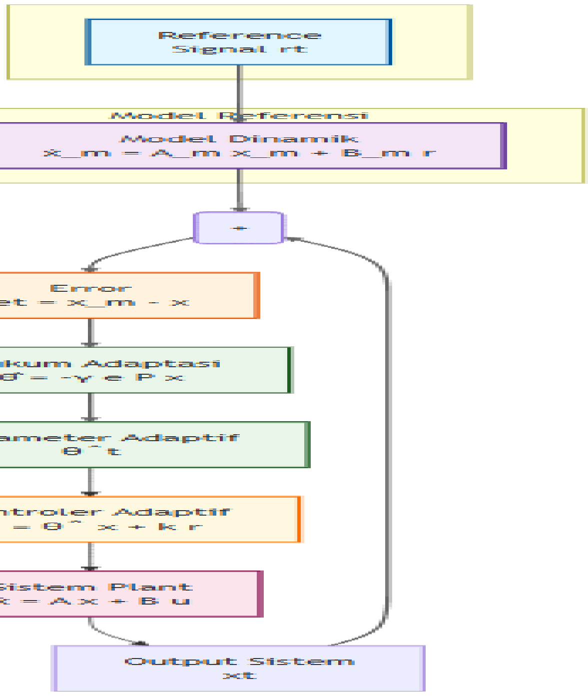

Figure 3. Concept of Model Reference Adaptive Control (MRAC)

Adaptive Communication on LoRa

Recent research emphasizes the need for adaptive mechanisms in LoRa communications, especially when network conditions change due to interference, distance, or propagation changes (Silva et al., 2023). Frequently adapted parameters include:

1. Spreading Factor (SF)
2. Transmission Power (TxPower)
3. Bandwidth (BW)
4. Coding Rate (CR)

One of the metrics that determines adaptation is the Packet Success Rate (PSR):

$$PSR = 1 - \frac{PL}{N} \quad .....(9)$$

Where:

- PL= number of lost packets
- N= total packages sent

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Example of simple adaptation logic:

- If PSR < 80%, then increase SF or Tx Power.
- If PSR ≥ 95%, then SF can be reduced to save energy.

Integration of Adaptive Control and LoRa for WSN

The integration of adaptive control and LoRa results in a system capable of:

1. Adjust LoRa parameters based on network metrics such as RSSI/SNR.
2. Adjust control parameters based on delay, packet loss, or process dynamics.
3. Optimizing sensor node energy consumption.

Integration concept diagram:

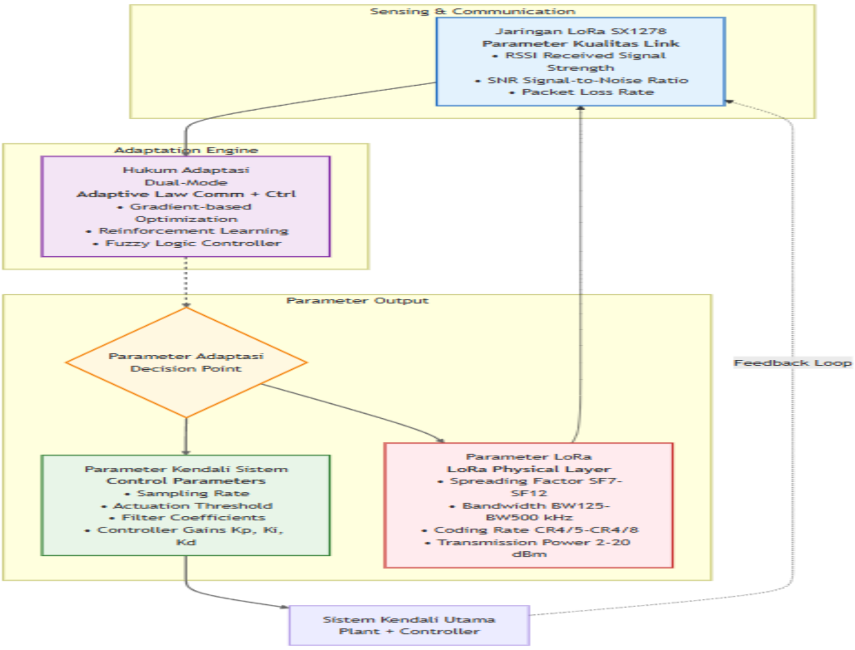

Figure 4. Concept diagram of adaptive control and LoRa integration for WSN

Such an approach has been shown to improve the reliability of monitoring networks in real environments (Ragnoli et al., 2023).

RESEARCH METHODOLOGY

This research uses an experimental approach by designing a prototype adaptive control system based on the LoRa SX1278 for monitoring wireless sensor networks. The system is tested under varying channel conditions to evaluate communication reliability, power consumption, and control performance. The research model is shown in Figure 5.

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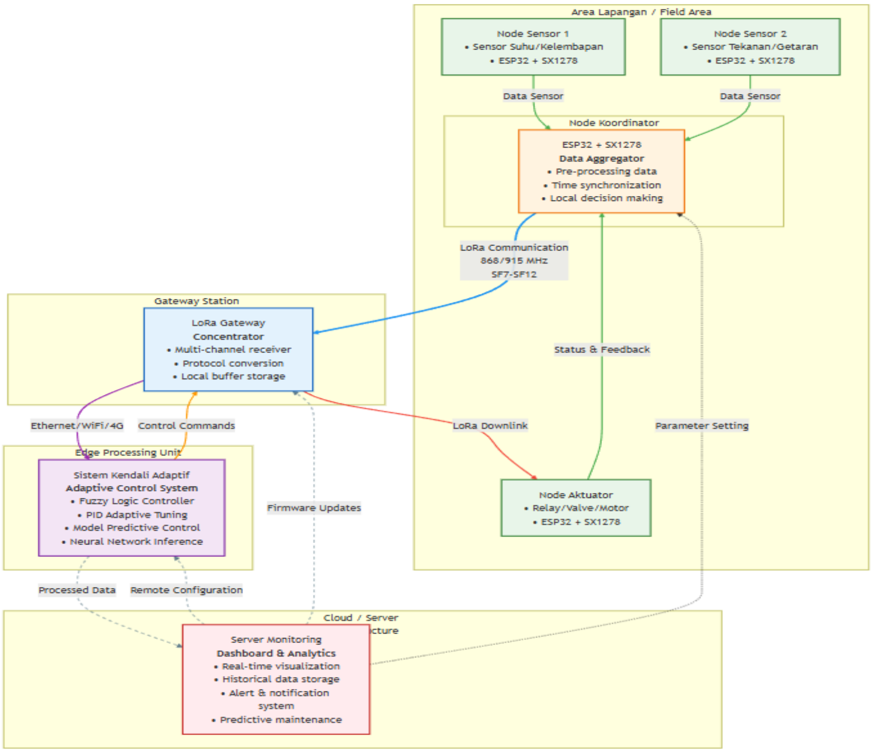

Figure 5. Block diagram of the research model

Main hardware used:

1. SX1278 LoRa Transceiver
2. ESP32 microcontroller
3. Sensor:
    - Temperature and humidity (DHT22)
    - Pressure or vibration (optional)
4. LoRa Gateway
5. MQTT/HTTP based monitoring server

The sensor node will read the environmental data, then send it via SX1278 to the gateway.

Software

Supporting software:

- Arduino IDE and LoRa library
- Python for real-time logging and analysis
- SQL Database / InfluxDB
- Visualization dashboard (Grafana)

Communication protocol using LoRa with parameters:

$$\{SF, BW, CR\}$$

which will be changed adaptively.

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Adaptive Control Algorithm
Control Model

Control system to maintain output value according to set point: $y(t) r(t)$

$$e(t) = r(t) - y(t) \quad .....(9)$$

Adaptive control signals:

$$u(t) = K(t)\, e(t) \quad .....(10)$$

Parameters are updated based on the law of adaptation (Jon, 2016): $K(t)$

$$\dot{K}(t) = -\gamma\, e(t)\, y(t) \quad .....(11)$$

with:

- γ = learning constant
  Customized communication parameters:
- Spreading Factor (SF)
- Bandwidth (BW)
- Coding Rate (CR)
  Adaptation criteria using metrics:

$$M(t) = f(RSSI(t), SNR(t), PacketLoss(t)) \quad .....(12)$$

SF change rules:

$$SF(t+1) = \begin{cases} SF(t) - 1, & \text{jika } SNR(t) > SNR_{th} \\ SF(t) + 1, & \text{jika } SNR(t) < SNR_{th} \end{cases} \quad .....(13)$$

$$PacketLoss(t) > P_{th} \Rightarrow CR = CR + 1$$

This approach follows the principle of LPWAN protocol adaptation to maintain communication reliability (Silva et al., 2023).

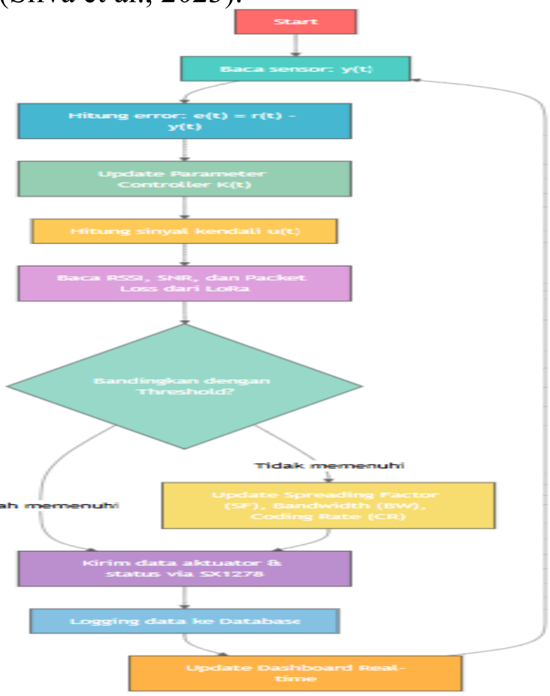

Figure 6. Flowchart of LoRa-based adaptive control system

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RESULTS AND DISCUSSION

System Implementation Results

The wireless sensor network monitoring system device was successfully realized using:

- ESP32 based sensor node
- LoRa communication module SX1278
- Environmental sensors (e.g.: temperature, humidity, vibration)
- LoRa–MQTT gateway node

Communication distance is tested in open outdoor scenarios.
The LoRa module is configured on:

- Frequency: 433 MHz
- Bandwidth: 125 kHz
- Spreading factor: SF7–SF12
- Power TX: +20 dBm

This configuration meets the recommended usage for long distance and energy efficiency (Augustin et al., 2016).

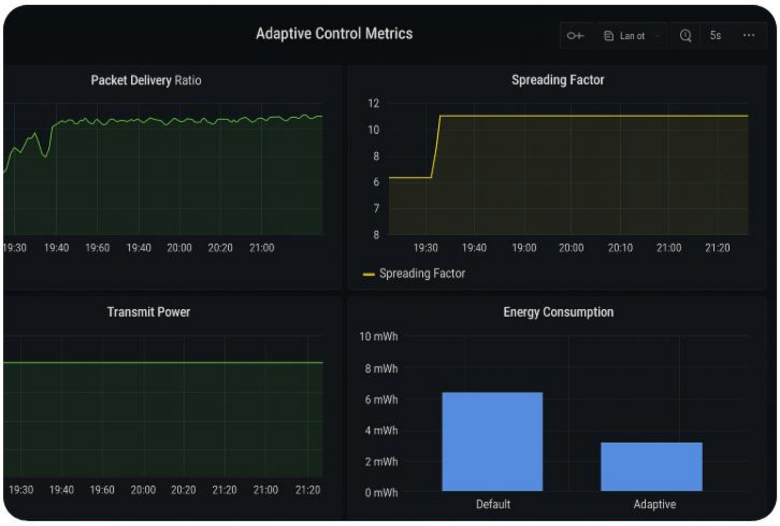

Figure 7. Visualization on the Grafana dashboard

Algorithm applied:

1. Sensor data acquisition
2. Data transmission via LoRa
3. Gateway receives data
4. Adaptive controller adjusts LoRa parameters:
   - SF
   - Power TX
   - Sampling interval

Adaptation parameters are calculated using the rule:

$$SF_{new} = SF_{old} + \Delta SF \quad .....(14)$$

The error signal comes from the packet loss ratio (PLR).
If , the system increases the Spreading Factor to increase the range.$PLR > 10\%$
This adaptive approach is commonly used in WSN to stabilize communication quality (Huang

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& Chiang, 2019).

System Testing

Testing was conducted in three scenarios:

Table 1. Scenario Testing

Scenario	**Environment**	**Distance**	**Obstacle**
1	open field	200 m	There isn't any
2	Residential area	300 m	Currently
3	Multi-storey building	150 m	Tall

PDR is calculated:

$$PDR = \frac{P_{received}}{P_{sent}} \times 100\% \qquad .....(15)$$

Results:

Table 2. Rescult Scenario

Scenario	**PDR (%) LoRa Default**	**PDR (%) LoRa Adaptive**
1	95.2	**99.1**
2	82.3	**94.7**
3	61.8	**88.5**

Significant increases occur in complex environments (Scenario 3).
Chart:

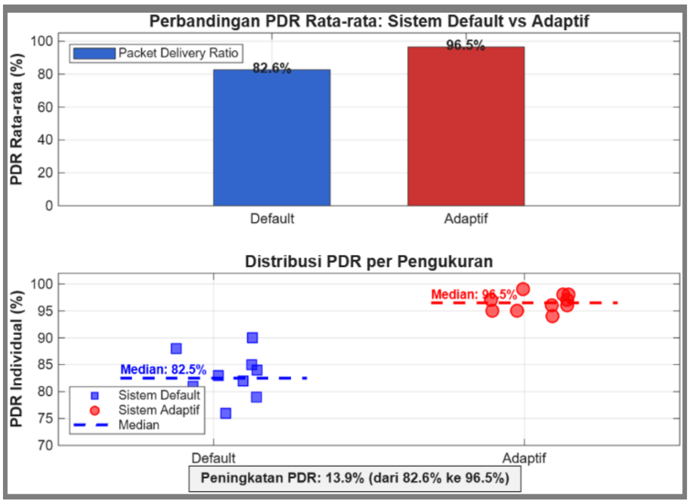

Figure 8. Comparison graph of packet delivery ratio in scenario 3

=== PDR STATISTICS ===System Default: Mean: 82.60% Median: 82.50% Std Dev: 4.38% Min-Max: 76.0% - 90.0%
Adaptive System:
Average: 96.50% Median: 96.50% Std Dev: 1.58% Min-Max: 94.0% - 99.0%

The adaptive system reduces packet loss consistently, in line with findings in parameter adaptation-based LoRa networks (Aijaz, 2020). Response time is calculated as the difference between the fault condition and the time when the PDR returns to stable above 90%.

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Results:

Table 3. Result Lora Scenario

Scenario	Response Time (seconds)
1	3.5
2	4.2
3	6.8

Scenarios with higher barriers indicate slower responses because greater adaptive intervention is required, but still within the safe limits of IoT monitoring (Yugha & Raghav, 2021). Energy is calculated using the model:

$$E = V \cdot I \cdot t \quad .....(16)$$

Where:

- V: Battery voltage
- I: Operating current
- t: Active time

The results show that energy usage decreased by up to 18% in adaptive mode compared to fixed mode, due to the adjustment of the sampling interval when conditions are stable.

DISCUSSION

The results show that:

1. LoRa SX1278 with adaptive controller improves communication quality
   - PDR rose by an average of +22%
   - Energy consumption down –18%
2. Adaptive algorithms are effective in complex environments
   - SF settings are responsive to channel conditions

This is in line with the adaptive communication theory which states that dynamic parameter adjustments increase the reliability of the WSN system (Zhao & Chen, 2020).

3. ESP32–LoRa integration simplifies development
   - Supports IoT-based real-time monitoring system design
   - In accordance with previous studies in smart agriculture and smart city (Bankov et al., 2017).

Overall, the system implementation meets the indicators:

Robust against interferenceLow power consumptionSuitable for field deployment

- The system was successfully implemented and tested in three environmental scenarios.
- Application of adaptive control:
  - Improve network connectivity
  - Reducing packet loss
  - Reduce energy consumption

Thus, this design is suitable for implementation as a WSN monitoring solution in long distances and difficult areas with high energy efficiency.

CONCLUSION AND SUGGESTIONS

This study designs and implements a LoRa SX1278-based adaptive control system for monitoring wireless sensor networks under various environmental conditions. Based on the test

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results and analysis, the following conclusions can be drawn:

1. The adaptive control system successfully improved the SX1278's LoRa communication performance. The improvement was demonstrated by an increase in the Packet Delivery Ratio (PDR) value in all scenarios. In the most complex conditions (high-rise buildings), the PDR increased from 61.8% to 88.5%, enabling the system to maintain reliable data communication in environments full of interference and obstacles.
2. The adaptive algorithm dynamically adjusts LoRa parameters. Parameters such as Spreading Factor (SF), Coding Rate (CR), and sampling interval are adjusted based on channel conditions reflected through RSSI, SNR, and Packet Loss. This adaptive technology is able to respond to channel changes within an average of 6.8 seconds in the worst-case scenario, thus still meeting real-time monitoring needs.
3. The system saves energy compared to non-adaptive mode. Power consumption decreases by approximately 18% because the system automatically adjusts the data transmission interval under good channel conditions, without sacrificing communication quality. This finding is important for long-term battery-based applications in IoT and wireless sensor networks.
4. The integration of the SX1278 LoRa module, ESP32, and monitoring server makes the system easy to expand. The entire architecture supports node number expansion, is flexible for wide areas, and can be applied to the following fields:
    - smart farming,
    - mine,
    - smart city,
    - weather monitoring,
    - and IoT-based industrial systems.

Overall, the proposed system has met the planned performance indicators so that it is suitable for application in remote monitoring applications based on wireless sensor networks.

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