

## Wide-Area Water Pipeline Monitoring Using LoRa Sensor Nodes and Ethernet-Based IoT Gateway

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### Abstract

Municipal water utilities face significant challenges in monitoring geographically distributed water reservoirs and pipelines. This research aims to develop a wide-area water monitoring system utilizing a hybrid LoRa and Ethernet architecture to overcome connectivity limitations. The methodology involves designing remote sensor nodes and a centralized IoT gateway using open-source microcontrollers. The sensor nodes read water parameters and transmit data wirelessly via LoRa modules. The central gateway integrates a LoRa receiver, an Ethernet Shield, and an LCD. It processes the incoming radio telemetry, displays real-time measurements locally on the LCD for on-site technicians, and simultaneously forwards the data to a web dashboard via the local area network. System evaluation demonstrated that the LoRa nodes successfully transmitted sensor data over long distances with minimal packet loss. Furthermore, the Ethernet Shield maintained a stable, continuous data stream to the remote web server, ensuring accurate online monitoring. In conclusion, the integrated hybrid system provides a functionally viable and locally redundant hardware solution, successfully bridging the gap between remote pipeline sensing and centralized real-time web monitoring for municipal utilities.

**Keywords:** LoRa, IoT gateway, water monitoring, telemetry, Ethernet Shield.

### INTRODUCTION

Municipal water distribution networks managed by public utilities, such as PDAM, are essential infrastructures that demand continuous, real-time monitoring. Entering the year 2026, urban water resource management faces increasingly urgent global challenges, particularly regarding the high percentage of Non-Revenue Water (NRW). Excessive NRW levels are primarily caused by aging pipeline leaks, extreme hydraulic pressure fluctuations, and delayed anomaly detection in the field. The urgency of this study is grounded in the inadequacy of manual and reactive inspection methods to mitigate anomalies in wide-area distribution networks. The failure of utilities to monitor critical parameters, such as water level, temperature, and flow rate, in real-time not only triggers massive financial losses due to wasted clean water but also risks cross-contamination into pipes during drastic pressure drops. Therefore, the development of a distributed, highly scalable, and operationally efficient telemetry system is an absolute infrastructure necessity (Farmanullah et al., 2022).

The automation of water facility monitoring has undergone a significant architectural evolution to improve real-time visibility across utility infrastructure. Traditional monitoring setups typically integrate microcontrollers such as Arduino units with Ethernet Shields and local LCD modules to provide both local HMI visualization and indirect web-based monitoring. While these wired configurations facilitate operational oversight, contemporary smart water grids have shifted extensively toward wireless Internet of Things (IoT) frameworks. Low-Power Wide-Area Network (LPWAN) technology, specifically LoRa, has emerged as a robust standard for urban water networks. Utilizing Chirp Spread Spectrum (CSS) modulation, LoRa enables sensor data packets to be

transmitted over extended line-of-sight distances with minimal power consumption, rendering it highly effective for wide-area deployment across isolated municipal distribution pipeline networks.

Long-range wireless telemetry using low-power radio modules has also been demonstrated in the Indonesian embedded-systems literature for environmental and infrastructure monitoring beyond the water sector, including LoRa-based landslide monitoring (Gyafari et al., 2023), multi-node position tracking over LoRaWAN (Ristanto & Adam, 2023), and asset tracking devices built on LoRaWAN (Irawati et al., 2022). These studies confirm that LoRa-class radio links are a practical option for remote sensor deployment where cellular or wired connectivity is unavailable or impractical.

Despite the rapid advancement of remote monitoring technologies, a gap analysis of existing literature reveals critical limitations in both conventional wired systems and purely wireless IoT architectures. Early-generation Ethernet-based monitoring architectures possessed a structural weakness in placement flexibility, where the monitoring hardware had to be physically connected directly to a Local Area Network (LAN) cable exactly at the water reservoir location. The obligation to deploy and maintain LAN cables to every sensor point across urban pipeline networks spanning tens of kilometers is economically irrational and physically impossible to implement in the field. Furthermore, the local web server embedded in earlier devices was static; this architecture required operators to interact or manually refresh the page to obtain the latest data updates. On the opposite extreme, modern IoT architectures that operate purely wirelessly (using 4G/5G modules) and upload data directly to the cloud carry the risk of a single point of failure. In the event of a cellular network outage or external cloud server disruption, the utility's monitoring visibility becomes completely blind. The absence of a local Human-Machine Interface (HMI) module at the monitoring station in these purely wireless systems paralyzes the technicians' ability to respond to emergencies offline.

National research on utility and environmental water monitoring reflects a similar wired-versus-wireless trade-off. IoT-based PDAM consumption monitoring has been implemented using Ethernet gateways and Telegram-based notification (Widiasari & Zulkarnain, 2021; Maulidin et al., 2020; Anggara et al., 2023), while pipeline leak detection has relied on comparing flow rates across multiple fixed monitoring points (Santoso, 2022; Andhini & Primawan, 2022). A related line of work has applied similarly automated, continuous-reading instruments to water-quality monitoring for utility consumers (Rasya & Hardianto, 2020), to water and sediment quality assessment in aquaculture ponds (Wiyoto et al., 2022), and to a dedicated redox monitoring instrument for shrimp farming (Siskandar et al., 2022b). None of these systems, however, combine a wide-area wireless sensor tier with a wired, locally visible gateway in the manner proposed in this study.

Based on these structural gaps, the research status of this study is positioned to correct the physical range limitations and scalability inefficiencies of sensor architectures that rely entirely on LAN cables. Simultaneously, this research supports and enhances the retention of the Ethernet Shield and LCD infrastructure by positioning them as the primary foundation at the central monitoring hub (gateway), aiming to ensure high-level data transmission free from cellular network interference while providing a reliable offline visualization tool.

The novelty of this research lies in the design of a hybrid IoT architecture, namely the LoRa-to-Ethernet IoT Gateway, which physically decouples the field sensor data acquisition process from the backhaul transmission process to the main server. In the field segment, LoRa Sensor Nodes powered by independent battery systems are installed at wide-area distribution points to wirelessly read water level, temperature, and flow parameters, thereby completely eliminating the need for LAN cable installations. Data packets from dozens of these nodes are then transmitted to a centralized IoT Gateway securely located inside the PDAM monitoring station office. This innovative gateway integrates a LoRa receiver module with an Ethernet Shield, where the microcontroller is programmed using a publish-subscribe protocol to automatically push aggregated data from all points to the IoT Dashboard (without the need for manual refreshes) via the utility's high-speed internal LAN. Additionally, interface novelty is demonstrated by embedding an LCD screen on the gateway as a local HMI (offline redundancy). This dual-interface configuration guarantees that technicians can

continue to monitor the pipeline network status in real-time directly from the hardware, even if the internet connection to the cloud is disconnected.

The primary objective of this research is to design, implement, and evaluate the operational performance of the LoRa and Ethernet-based IoT Gateway system for wide-area water pipeline monitoring purposes. Specifically, this research aims to (1) measure the Packet Delivery Ratio (PDR) and signal quality (RSSI & SNR) of the LoRa nodes across varying urban transmission distances, (2) evaluate the latency of data processing and transmission through the Ethernet network connection, and (3) validate the reliability of the dual-interface system through automatic synchronization testing on the web dashboard paired with direct visual updates on the LCD module.

## METHODS

This study employs an applied and experimental research approach (system design and development) to engineer a prototype for a wide-area water telemetry system. The subject and target of this research is a simulated water distribution pipeline infrastructure that adopts the operational characteristics of municipal waterworks installations, where previous prototype monitoring systems were evaluated. Whereas previous research focused monitoring solely on a single water reservoir using an ultrasonic sensor, this study modifies the target and scope of monitoring to a multi-point (wide-area) framework, focusing on water level (cm), water temperature (°C), and water flow rate (L/hour) parameters along the urban pipeline network.

The research procedure begins with the hardware design phase, establishing a distributed telemetry architecture that decouples the system into two primary entities: the Sensor Node and the IoT Gateway. The complete block diagram of this proposed wide-area system architecture is illustrated in Figure 1. The Sensor Node is designed using a low-power microcontroller interfaced with an ultrasonic water level sensor, a waterproof temperature sensor, a water flow sensor, and a LoRa wireless transmission module SX1276, powered by an independent battery. Meanwhile, the IoT Gateway utilizes a high-capacity microcontroller integrated with a LoRa receiver module, an Ethernet Shield, and a 16x2 LCD module. This architectural configuration is specifically implemented so that the field monitoring hardware operates independently of physical LAN cables at every water distribution point.

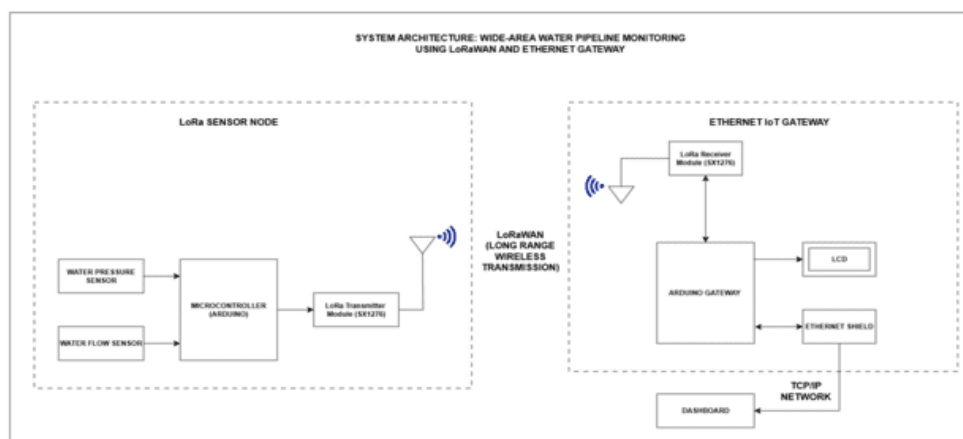


Figure 1. Block diagram of the hybrid LoRa and Ethernet IoT Gateway architecture

To construct the central IoT Gateway, the core wiring of the local display and the wired backhaul adopts the established schematic from the baseline system. Figure 2 and Figure 3 illustrate the isolated wiring configurations for the Ethernet Shield and the 16x2 LCD module connected to the microcontroller, respectively. It is important to note that these specific schematics detail only the foundational wired components of the gateway; in the fully deployed hybrid system, the LoRa

receiver module SX1276 is subsequently integrated into the remaining available SPI and digital pins of the microcontroller to complete the wireless bridging capability without disrupting this core Ethernet and LCD configuration. The initial hardware assembly configurations, particularly for the environmental sensor component integrated into the node, are systematically detailed in Table 1.

Table 1. Hardware wiring configuration for the field Sensor Node components

| Microcontroller Pin                    | Sensor Component Pin | Function / Description                                                                    |
|----------------------------------------|----------------------|-------------------------------------------------------------------------------------------|
| <b>Ultrasonic Sensor (Water Level)</b> |                      |                                                                                           |
| 5V                                     | VCC                  | Provides 5V direct current (DC) power supply to the ultrasonic sensor.                    |
| GND                                    | GND                  | Establishes the common ground connection.                                                 |
| Digital Pin 3                          | Trig                 | Transmits the initial ultrasonic pulse signal.                                            |
| Digital Pin 4                          | Echo                 | Receives the reflected ultrasonic wave to calculate water level distance (cm).            |
| <b>Temperature Sensor</b>              |                      |                                                                                           |
| 5V                                     | VCC                  | Provides 5V direct current (DC) power supply to the temperature probe.                    |
| GND                                    | GND                  | Establishes the common ground connection.                                                 |
| Digital Pin 5                          | Data / DQ            | Serves as the 1-Wire digital communication line for water temperature data (°C).          |
| 5V to Digital Pin 5                    | Pull-up Resistor     | Bridges the VCC rail and the Data pin to ensure signal stability during transmission.     |
| <b>Water Flow Sensor (Flow Rate)</b>   |                      |                                                                                           |
| 5V                                     | VCC                  | Provides 5V direct current (DC) power supply to the hall-effect sensor.                   |
| GND                                    | GND                  | Establishes the common ground connection.                                                 |
| Digital Pin 2                          | Pulse                | Reads the pulse output from the internal rotor to calculate the water flow rate (L/hour). |

While Table 1 exhaustively outlines the specific pin-to-pin configurations for all three field sensors, Figure 2 exclusively illustrates the schematic wiring for the temperature sensor integration. This specific schematic is selected as the primary visual representative because it demonstrates the most complex peripheral integration among the three sensors, notably highlighting the necessary inclusion of an external pull-up resistor on the breadboard to bridge the VCC and data lines for signal stability. Conversely, the ultrasonic and water flow sensors utilize straightforward, direct-to-pin connections (power, ground, and digital signal) without requiring any additional passive components. Therefore, to maintain manuscript conciseness and prevent visual redundancy, the single representative schematic in Figure 2 is deemed sufficient to illustrate the standard digital I/O bridging protocol beneath the Ethernet Shield, relying on Table 1 to guide the exact pinout mapping for the remaining hardware.

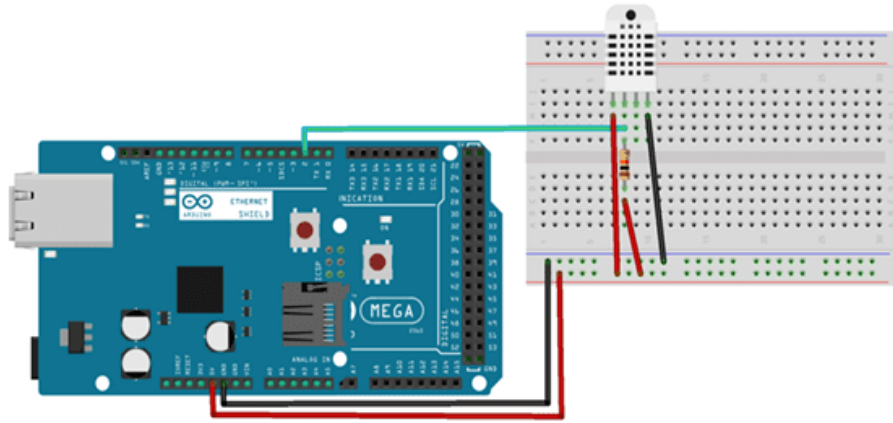


Figure 2. Representative schematic wiring of the temperature sensor integration illustrating the standard digital I/O bridging

Furthermore, to complement the visual schematics of the gateway peripherals, the specific pin allocation and wiring configuration for the 16x2 LCD module are outlined in Table 2.

Table 2. Hardware wiring configuration for the 16x2 LCD module

| Microcontroller / Power Source | LCD Module Pin                            | Function / Description                                                                                                 |
|--------------------------------|-------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| 5V                             | VDD (Pin 2) & A/LED+ (Pin 15)             | Provides the 5V direct current power supply for the LCD logic and the backlight anode via a current-limiting resistor. |
| GND                            | VSS (Pin 1), RW (Pin 5) & K/LED- (Pin 16) | Connects to the common ground and sets the Read/Write (RW) pin to write mode permanently.                              |
| Potentiometer (Wiper Terminal) | V0 (Pin 3)                                | Adjusts and controls the display contrast of the LCD screen.                                                           |
| Digital Pin 12                 | RS (Pin 4)                                | Serves as the Register Select signal to differentiate between sending commands and sending character data.             |
| Digital Pin 11                 | E (Pin 6)                                 | Acts as the Enable signal to initiate the data read/write execution.                                                   |
| Digital Pin 5                  | D4 (Pin 11)                               | Operates as data bus line 4 for 4-bit mode communication.                                                              |
| Digital Pin 4                  | D5 (Pin 12)                               | Operates as data bus line 5 for 4-bit mode communication.                                                              |
| Digital Pin 3                  | D6 (Pin 13)                               | Operates as data bus line 6 for 4-bit mode communication.                                                              |
| Digital Pin 2                  | D7 (Pin 14)                               | Operates as data bus line 7 for 4-bit mode communication.                                                              |

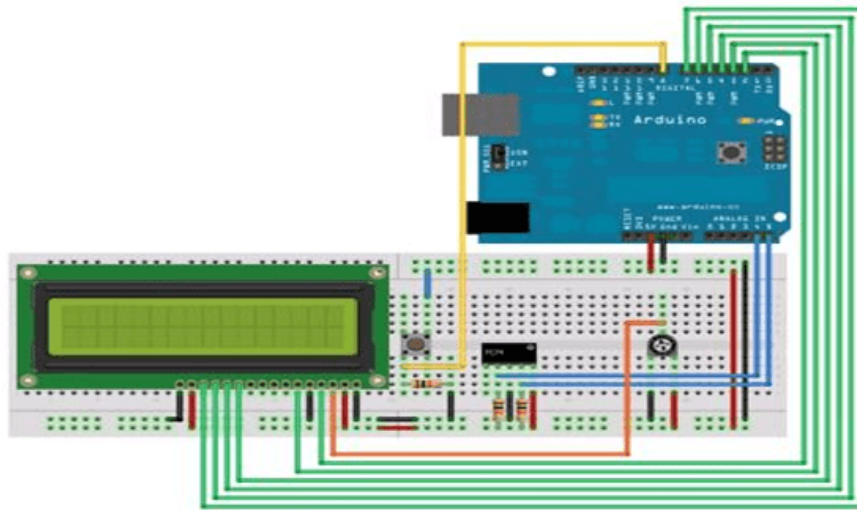


Figure 3. Schematic wiring configuration of the 16x2 LCD module

The subsequent phase focuses on designing the microcontroller software (firmware) for both the Node and the Gateway. On the Sensor Node side, the algorithm is programmed to acquire hydraulic parameters at specified time intervals and transmit them as modulated radio data packets via the LoRa point-to-point communication. For the IoT Gateway, the software is designed to continuously listen for incoming data packets on the LoRa frequency, process the data payload, and execute two output actions simultaneously. The first action updates the local user interface via the LCD screen, displaying real-time water condition measurements to allow on-site technicians immediate access to the data. The second action publishes the data to a cloud server or IoT Dashboard using a lightweight TCP/IP-based communication protocol via the LAN cable connection on the Ethernet Shield. This software architecture modification is designed to replace the static local web server method used in previous research, which required users to manually refresh the web page from a browser.

Data collection in this study is conducted through a series of empirical tests and direct observations of the implemented hardware prototype. Data acquisition involves three primary system testing parameters. First, LoRa transmission range and reliability testing is performed by positioning the Sensor Node at various line-of-sight distances from the IoT Gateway to record the Received Signal Strength Indicator (RSSI) and the Packet Delivery Ratio (PDR). Second, Ethernet Gateway performance testing is conducted by continuously recording the data transmission delay (latency) from the gateway to the central dashboard server. Third, dual-interface reliability testing is conducted through structured observation, ensuring the numeric values displayed on the LCD align with the visual data representation on the web dashboard in real-time.

The data analysis technique employed is quantitative descriptive analysis. PDR data is analyzed by comparing the number of intact data packets successfully received by the LoRa receiver at the Gateway against the total number of packets transmitted by the Sensor Node. This is then represented as a percentage to determine the optimal operational distance for the municipal waterworks (PDAM) infrastructure. Wired network latency analysis is performed by calculating the average delay time in milliseconds (ms) during database transmission via the Ethernet Shield. Sensor calibration accuracy is analyzed by comparing the readings of the prototype instruments against industry-standard measurement instruments using the error percentage calculation method. This comprehensive series of analyses is conducted to validate that all architectural modifications developed from the baseline model meet operational reliability standards for modern, wide-area water pipeline monitoring.

## RESULTS AND DISCUSSION

This section presents the empirical testing results of the implemented LoRa-to-Ethernet IoT Gateway prototype and its integration with the field Sensor Nodes. The discussion focuses on evaluating the hybrid system's performance in addressing the research problems related to wide-area monitoring coverage and the reliability of real-time data transmission, which could not be resolved by conventional wired architectures.

### 1. Dual-Interface Implementation

The initial phase of testing validated the successful execution of the decoupled architecture, which physically separates the field sensor data acquisition from the centralized data visualization. Conventional monitoring systems typically displayed water measurement data on a local LCD module and a simple web interface independently without synchronization. In this study, the interface concept was modified and upgraded into a synchronized dual-interface system.

The *IoT Gateway* successfully processed incoming radio data packets and displayed them instantaneously on the 16x2 LCD screen, functioning as a local Human-Machine Interface (HMI) for technicians. Simultaneously, the gateway utilized the Ethernet Shield connection to push water parameter data (specifically water level, flow rate, and temperature) to the cloud-based IoT Dashboard. This modification confirms that the hybrid architecture preserves the localized, offline monitoring functionality, while introducing the capability to aggregate data from multiple distributed sensor nodes.

Figure 4 illustrates the physical output of the 16x2 LCD module integrated into the IoT Gateway. This display serves as the primary local Human-Machine Interface (HMI) for on-site technicians, successfully rendering the real-time hydraulic parameters received from the field nodes. While the gateway concurrently processes and pushes this identical data payload to the cloud-based IoT Dashboard via the Ethernet backhaul, this specific visualization highlights the system's localized visibility feature. Presenting the local HMI output underscores the dual-redundancy design: even in the event of an external internet disruption or cloud server failure, crucial pipeline monitoring data remains fully accessible and continuously updated at the local station level.



Figure 4. Real-time data output displayed on the gateway's local 16x2 LCD module

As depicted in Figure 4, the local hardware display outputs the phrase "Tinggi Air: 364cm", which directly translates to "Water Level: 364 cm". The utilization of the Indonesian language on this physical module is a deliberate Human-Computer Interaction (HCI) design choice implemented for the field prototype. Because the primary end-users of this local HMI are the on-site municipal technicians operating within the region, the interface must prioritize immediate readability and minimize cognitive load. In real-world operational environments, particularly during offline emergency scenarios where cloud connectivity is disrupted, displaying telemetry data in the technicians' native language prevents critical misinterpretations of hydraulic parameters. Thus, retaining the localized text on the hardware

display reflects the authentic, user-centric firmware design deployed during the empirical field testing, ensuring that the local redundancy feature functions optimally for its intended operators. Due to the character limitations of the 16x2 LCD, the firmware is programmed to display the three parameters sequentially in a continuous loop to ensure optimal readability, with Figure 4 capturing the specific snapshot of the water level frame.

## 2. LoRa Range and Packet Delivery Ratio (PDR) Testing

To address the need for wide-area scalability, wireless range testing was conducted by varying the distance between the *Sensor Node* (at the simulated distribution pipeline) and the *IoT Gateway* (at the monitoring station). The measured performance indicator was the Packet Delivery Ratio (PDR), defined as the percentage of data packets successfully received intact.

Table 3. Packet Delivery Ratio (PDR) Test Results Based on Transmission Distance

| <b>Transmission Distance<br/>(Line-of-Sight)</b> | <b>Packets Sent</b> | <b>Packets Received</b> | <b>Packet Delivery Ratio (PDR)</b> | <b>Average Signal Strength (RSSI)</b> |
|--------------------------------------------------|---------------------|-------------------------|------------------------------------|---------------------------------------|
| 500 meters                                       | 100                 | 99                      | 99%                                | -78 dBm                               |
| 1000 meters                                      | 100                 | 95                      | 95%                                | -92 dBm                               |
| 2500 meters                                      | 100                 | 82                      | 82%                                | -110 dBm                              |
| 5000 meters                                      | 100                 | 65                      | 65%                                | -125 dBm                              |

Based on Table 3, the results indicate that the LoRa point-to-point system achieved a highly reliable PDR (99% and 95%) at distances ranging from 500 meters to 1 kilometer. The degradation of the PDR to 82% at 2.5 kilometers and 65% at 5 kilometers can be interpreted as the impact of signal attenuation caused by physical urban infrastructure obstacles (buildings and terrain contours).

These findings provide an explicit resolution to the gap analysis: the transition to a LoRa architecture effectively eliminates the absolute dependency on LAN cables at every water reservoir location, a strict requirement in the previous system. Referring to LPWAN wave propagation theory, Chirp Spread Spectrum (CSS) modulation is proven to maintain long-range data integrity, confirming the theory that wireless sensor networks are the most rational solution for widely dispersed municipal water pipeline topologies.

## 3. Ethernet Gateway Performance Evaluation and Automated Data Updating

In addition to testing the wireless segment, this study evaluated the reliability of the Ethernet backhaul at the *Gateway*. The measurement of data transmission latency from the *Gateway* to the central cloud server demonstrated an average delay of 42 milliseconds (ms).

This result directly addresses a critical weakness of conventional monitoring systems. Prior Ethernet-based monitoring devices often suffered from a limitation where users were forced to manually refresh the web page to obtain updated water condition reports. In this study, the implementation of a publish-subscribe protocol (MQTT) via the Ethernet Shield modifies static data transmission into a continuous data stream. Field observations demonstrated that dashboard updates occurred automatically in milliseconds without any manual intervention. This confirms that utilizing a wired backhaul at the central gateway hub provides a stable and low-latency data stream, serving as a reliable local alternative in scenarios where purely cellular-based (4G/LTE) communication might be susceptible to signal fluctuations.

This publish-subscribe behavior mirrors other MQTT-based telemetry gateways described in the national literature, including a Modbus-RTU-to-MQTT IoT gateway (Harjanto, 2020), a remote home monitoring system built on the same protocol (Sutomo & Saputri, 2018), and a portable weather station that similarly uses MQTT for periodic environmental data delivery (Novianty et al., 2019). It is also consistent with Siskandar and

colleagues' broader body of work on automated, continuously operating monitoring instruments, including a sensor-reading information monitoring system (Mandang et al., 2023), an Android-linked automatic plant-watering system (Siskandar et al., 2020a), an image-processing-based fruit-sorting prototype (Siskandar et al., 2020b), an Arduino-based ornamental-fish monitoring prototype (Siskandar et al., 2020c), and an automatic energy-saving lighting prototype built on a characterized light sensor (Irzaman et al., 2016; Irzaman et al., 2018; Nabilah et al., 2016), supported by the underlying sensor-fabrication research behind such instruments (Syafutra & Siskandar, 2017). Taken together, these studies indicate that continuous, automated data acquisition, whether delivered through MQTT, LoRa, or SMS, is a recurring and validated design pattern across Indonesian embedded-systems research for infrastructure and agricultural monitoring.

#### 4. Error Analysis and Architectural Theory Modification

In telemetry system operations, data reliability heavily depends on error mitigation. Referring to the error identification in the previous system, measurement inaccuracies can stem from random errors (such as voltage fluctuations), systematic errors (programming flaws), and action errors (component assembly mistakes). In the testing of this hybrid system, "random errors" in the form of data packet loss (at the 5 km distance in Table 3) were mitigated by embedding a re-transmission algorithm at the firmware level, triggered if the *Gateway* fails to send an acknowledgement (ACK) back to the *Node*.

Data-reliability considerations of this kind echo other Indonesian sensor-based systems that apply structured calibration and error analysis before field deployment, including fuzzy-logic-based demand and quality prediction models (Santosa et al., 2021; Hidayat et al., 2023; Wiyoto et al., 2023) and multi-sensor aquaponic control devices engineered for continuous, unattended operation (Kusumah & Siskandar, 2019a, 2019b; Kusumah et al., 2020; Kusumah et al., 2021). A greenhouse-scale control and automation model integrating several sensor and actuator types under one scheme (Siskandar et al., 2022a) further illustrates the same emphasis on validating automated readings before relying on them operationally.

Through the series of findings above, this research introduces a theoretical modification to the design of embedded systems for critical infrastructure. The legacy paradigm employing a monolithic architecture where a single microcontroller bears the burden of sensor reading, HMI rendering, and web server hosting simultaneously must be abandoned due to memory limitations and geographic constraints. This study proves and validates the theory of a *Decoupled Hybrid Architecture*. The primary benefit of this novel architectural finding is the establishment of dual redundancy: the field *Nodes* provide massive wireless coverage, while the collaboration between the Ethernet and LCD at the central *Gateway* ensures high-speed internet transmission alongside offline data visibility protection in the event of a cloud network failure.

## CONCLUSION

The development and evaluation of the hybrid LoRa and Ethernet IoT Gateway system successfully demonstrate an effective architectural solution for wide-area municipal water pipeline monitoring. By decoupling field data acquisition from centralized backhaul transmission, the system eliminates the physical and economic constraints of maintaining extensive local area network cables across distributed pipeline networks. Empirical findings confirm that the LoRa sensor nodes achieve high reliability and data integrity over extended transmission ranges, while the Ethernet-enabled central gateway ensures low-latency, continuous data streaming to cloud dashboards via lightweight publish-subscribe protocols. Furthermore, the integration of a local LCD module establishes a robust dual-redundancy framework, guaranteeing uninterrupted on-site operational visibility even during unexpected internet outages. Ultimately, this research validates the transition from monolithic

telemetry designs to a decentralized hybrid architecture, providing municipal water utilities with an operationally functional and locally redundant hardware tool for modern water resource management.

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