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HYBRID ESP-NOW AND MQTT-BASED MONITORING AND EARLY WARNING SYSTEM FOR RRI MANADO TRANSMITTER ROOM

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Abstract

The transmitter room of LPP RRI Manado is a vital operational center housing high-power electronic equipment susceptible to damage from temperature fluctuations, humidity instability, abnormal machine noise, and fire hazards. Currently, no automated monitoring system has been implemented to continuously observe environmental conditions in real-time, resulting in delayed detection of technical anomalies. This research aims to design and implement an IoT-based monitoring and early warning system for the transmitter room environment. *The novelty of this system lies in its hybrid ESP-NOW and MQTT communication architecture, specifically tailored for the multi-parameter environmental monitoring demands of broadcast transmitter facilities, where neither protocol alone could fulfill both low-latency local transmission and real-time remote dashboard access simultaneously.* The system employs ESP-NOW for wireless inter-building data transmission and MQTT for real-time integration to a web-based monitoring dashboard. *Environmental parameters were selected based on the primary physical risk factors in high-power electronic environments: temperature and humidity (DHT22) to detect thermal and moisture anomalies, sound intensity (GY-MAX4466) to identify mechanical failure indicators, and smoke concentration (MQ-2) as an early fire hazard indicator.* The research method used is quantitative with an experimental approach, *whereby numerical data were collected from sensor readings and communication performance tests, then analyzed to evaluate system accuracy, latency, and packet loss.* The expected outcome is a system that enables centralized monitoring for TMB technicians and delivers early warning notifications when abnormal conditions are detected, ensuring operational reliability and continuity of LPP RRI Manado broadcast services.

Keywords: Internet of Things; ESP-NOW; MQTT; Monitoring; Early Warning System

Abstrak

Ruang pemancar LPP RRI Manado merupakan pusat operasional vital yang berisi perangkat elektronik berdaya tinggi yang rentan terhadap kerusakan akibat fluktuasi suhu, ketidakstabilan kelembapan, kebisingan mesin yang tidak normal, dan potensi kebakaran. Saat ini, belum ada sistem pemantauan otomatis yang telah diimplementasikan untuk mengamati kondisi lingkungan secara kontinu dan real-time, sehingga anomali teknis sering kali terlambat dideteksi. Penelitian ini bertujuan untuk merancang dan mengimplementasikan sistem monitoring dan peringatan dini berbasis Internet of Things (IoT) untuk lingkungan ruang pemancar. Kebaruan sistem ini terletak pada arsitektur komunikasi hybrid ESP-NOW dan MQTT yang dirancang khusus untuk kebutuhan pemantauan lingkungan multi-parameter di fasilitas ruang pemancar siaran, di mana tidak ada satu protokol pun yang dapat memenuhi kebutuhan transmisi lokal berlatensi rendah dan akses dashboard jarak jauh secara real-time sekaligus. Sistem ini menggunakan ESP-NOW untuk transmisi data nirkabel antar-gedung dan MQTT untuk integrasi real-time ke dashboard pemantauan berbasis web. Parameter lingkungan dipilih berdasarkan faktor risiko fisik utama di lingkungan elektronik berdaya tinggi: suhu dan kelembapan (DHT22) untuk mendeteksi anomali termal dan kelembapan, intensitas suara (GY-MAX4466) untuk mengidentifikasi indikator kerusakan mesin, dan konsentrasi asap (MQ-2) sebagai indikator dini bahaya kebakaran. Metode penelitian yang digunakan adalah kuantitatif dengan pendekatan eksperimental, di mana data numerik dikumpulkan dari pembacaan sensor dan pengujian performa komunikasi, kemudian dianalisis untuk mengevaluasi akurasi sistem, latensi, dan packet loss. Hasil *yang diharapkan adalah sistem yang memungkinkan pemantauan terpusat bagi teknisi TMB dan memberikan notifikasi peringatan dini ketika kondisi abnormal terdeteksi, memastikan keandalan operasional dan keberlangsungan layanan siaran LPP RRI Manado.*

Kata kunci: Internet of Things; ESP-NOW; MQTT; Monitoring; Peringatan Dini

INTRODUCTION

The transmitter room of LPP RRI Manado serves as a vital operational center housing various high-power electronic devices. As the heart of the public broadcast service, this environment is exposed to significant risks of equipment damage caused by physical factors such as extreme temperature fluctuations, unstable humidity, abnormal machine noise, and fire hazards(Fasya, Zaenudin, Muhamad Masjun Efendi, & Lalu Delsi Samsumar, 2024).

To date, no automated monitoring system has been available to continuously observe the environmental conditions of the transmitter room. This situation causes technical anomalies to frequently go undetected in their early stages, resulting in delayed responses. Such delays pose the risk of fatal damage to transmitter equipment, ultimately disrupting the continuity of LPP RRI Manado's public broadcast services (Maulana, Ramadhan, Maharani, & Maulana, 2023).

Several previous studies have explored IoT-based environmental monitoring systems in various contexts. Basir et al. (2023) developed a temperature and humidity monitoring system using MQTT protocol, while Sholicha & Budi (2024) proposed a hybrid communication architecture combining ESP-NOW and MQTT for low-latency data transmission. However, these studies were conducted in general-purpose environments and did not address the specific operational demands of broadcast transmitter rooms, where simultaneous monitoring of multiple critical parameters — including acoustic anomalies and smoke detection — is essential. Furthermore, most existing systems lack an integrated Early Warning System (EWS) capable of real-time automated alerts to technical personnel. This research gap motivates the present study.

The Internet of Things (IoT) offers a solution by enabling the integration of physical sensors into digital systems for real-time monitoring (Basir, Pratama, & Aminullah, 2023).By leveraging a hybrid protocol architecture that combines ESP-NOW and MQTT, sensor data can be transmitted efficiently from the field to a web-based monitoring dashboard (Sholicha & Budi, 2024).

This research aims to design and build an IoT-based monitoring and Early Warning System (EWS) for the transmitter room of LPP RRI Manado. The parameters monitored include temperature and humidity (DHT22), sound intensity (GY-MAX4466), and smoke presence (MQ-2). The system is expected to automatically notify New Media Technology (TMB) technicians upon detection of abnormal conditions, thereby preventing further damage to the broadcast infrastructure.

RESEARCH METHODS

This research focuses on the design and implementation of a hybrid-based monitoring and early warning system for physical parameters in the transmitter room of LPP RRI Manado. The system integrates ESP-NOW for low-latency local communication and MQTT protocol for remote data transmission via the internet. The research methodology covers system design, hardware and software development, data acquisition, and system performance evaluation. Furthermore, testing is conducted to measure communication reliability, including latency and packet loss, as well as the accuracy of sensor readings compared to standard measurement instruments.

The experimental setup consists of two ESP32 microcontroller nodes. The first node (sensor node) is deployed in the transmitter room, collecting environmental data from three sensors: a DHT22 sensor for temperature and humidity measurement, a GY-MAX4466 microphone module for sound intensity detection, and an MQ-2 gas sensor for smoke and combustible gas presence. The second node (gateway node) is located in the TMB technician room, receiving data from the sensor node via ESP-NOW protocol and forwarding it to a cloud-based MQTT broker over a Wi-Fi internet connection. This node is also equipped with a buzzer connected to GPIO 27, which activates automatically upon receiving abnormal condition data as a local audible alert. The sensor node transmits data packets to the gateway node at a defined interval, after which the gateway publishes the data to the MQTT broker for real-time display on the web-based monitoring dashboard. The DHT22 is connected to the ESP32 data pin (GPIO 4),

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the GY-MAX4466 analog output is connected to the ADC pin (GPIO 34), and the MQ-2 analog output is connected to the ADC pin (GPIO 35). Both ESP32 nodes are powered via DC adapter and operate on the 2.4 GHz Wi-Fi band.

Types of Research

This research employs a quantitative method with an experimental approach. The quantitative method was chosen based on the need to objectively measure system performance through numerical data generated by the device's sensors, including Packet Loss and Latency testing on the ESP-NOW and MQTT hybrid protocol, as well as sensor accuracy testing compared against standard measurement instruments (Wicaksono & Rahmatya, 2022).

Time and Place of Research

The research, data collection, and system implementation were conducted at the Transmitter Room of LPP RRI Manado. This location was selected because it serves as a vital operational center housing high-power electronic equipment that requires continuous environmental monitoring. The entire research process was planned to run for approximately two (2) months, commencing in January 2026.

Research Target / Subject

The subject of this research is an IoT-based monitoring system implemented at the transmitter room of LPP RRI Manado. The observed objects are physical environmental parameters including temperature, humidity, machine noise intensity, and smoke concentration. The end-users of this system are the New Media Technology (TMB) technicians of LPP RRI Manado.

Procedure

The research procedure covers the following stages:

(1) Literature study: collecting references on IoT, ESP-NOW and MQTT protocols, and technical component specifications. (2) System design: designing the hardware circuit schematic, hybrid communication architecture, and web-based dashboard interface. (3) Implementation: assembling electronic components using a breadboard, programming the ESP32, and setting up the MQTT broker server. (4) Testing and evaluation: sensor accuracy testing, communication range testing, and early warning system mechanism verification. The overall system architecture is illustrated in Figure 1, showing the data flow from the sensor node in the transmitter room to the web-based monitoring dashboard via ESP-NOW and MQTT protocols.

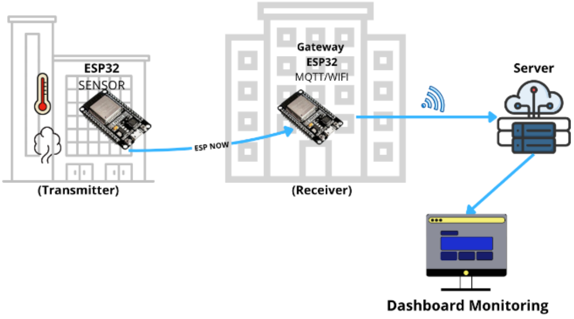

Figure 1. System Architecture of IoT-based Monitoring and Early Warning System

Data, Instruments, and Data Collection Techniques

Data were collected from three types of sensors: the DHT22 for temperature (range -40°C to 80°C) and humidity (0%–100%), the GY-MAX4466 for sound intensity in decibels (dB), and the MQ-2 for smoke and flammable gas detection. Data were transmitted wirelessly using the ESP-NOW protocol between buildings and the MQTT protocol to the monitoring server. Data collection was performed automatically and continuously by the IoT system (Rumampuk, Poekoel, & Rumagit, 2021).

Data Analysis Technique

Data analysis was conducted quantitatively by comparing sensor readings against standard measurement instruments (calibration), analyzing data communication performance through packet loss and latency measurements, and evaluating the system's response time in delivering early warnings when sensor values exceeded the predefined threshold.

RESULTS AND DISCUSSION

Prior to system implementation, a comparative analysis of candidate sensors was conducted to justify the selection of components used in this study. For temperature and humidity measurement, the DHT22 was selected over the DHT11 due to its superior accuracy (±0.5°C and ±2–5% RH compared to ±2°C and ±5% RH for the DHT11) and wider measurement range (-40°C to 80°C). For sound intensity detection, the GY-MAX4466 microphone module was preferred over the KY-037 and LM393 modules because of its adjustable gain potentiometer and more stable analog output, which is critical for reliable dB-level readings in an industrial environment. For gas and smoke detection, the MQ-2 sensor was selected over the MQ-135 and MQ-7 because it simultaneously detects multiple hazardous substances relevant to the transmitter room context, including LPG, smoke, and combustible gases. These selection criteria ensured that the chosen sensors provide the best balance of accuracy, reliability, and suitability for the specific monitoring demands of the LPP RRI Manado transmitter room environment.

System Architecture

The designed monitoring system consists of two ESP32 nodes placed in different buildings. The first node (sensor node) is responsible for reading data from the DHT22, GY-MAX4466, and MQ-2 sensors, then transmitting the data directly to the second node using the ESP-NOW protocol. The second node (gateway node) receives data from the sensor node and forwards it to the monitoring server via MQTT over a Wi-Fi connection.

This hybrid architecture proved effective in optimizing two distinct communication layers: ESP-NOW at the local layer for power efficiency and inter-node range, while MQTT serves as the integration bridge to the internet. With this architecture, data from the transmitter room area can be accessed globally through a web interface without burdening each sensor node with a direct internet connection. This approach is consistent with similar IoT-based server room monitoring implementations that utilize ESP32 and MQTT for centralized environmental data acquisition (Begti Rizal Nugroho et al., 2025; Ilmi, Sasmoko, Suasana, Sulartopo, & Putra, 2024; Pasic, Kuzmanov, & Atanasovski, 2021; Zhang et al., 2024).

Sensor Accuracy Testing

Accuracy testing was carried out by comparing the readings of each sensor against a standard reference over 10 trials under controlled environmental conditions, a number considered sufficient to obtain stable average readings and minimize random measurement error in sensor validation testing. The DHT22 sensor was compared against a certified digital thermometer and hygrometer, while the GY-MAX4466 was compared against a sound level meter. MQ-2 testing was conducted qualitatively using a controlled smoke source, as no calibrated gas concentration reference instrument was available during the testing period.

The calibration procedure for the DHT22 sensor was conducted by placing the sensor in the same enclosed space as the reference thermometer and hygrometer for a stabilization period of 5 minutes prior to each reading, ensuring thermal equilibrium between the sensor and the reference instrument. For the GY-MAX4466 microphone module, calibration was performed by positioning both the sensor and the reference sound level meter at a fixed distance of 30 cm from the sound source, using a consistent audio tone as the stimulus. The MQ-2 sensor calibration was conducted qualitatively by exposing the sensor to smoke generated from a controlled source at a fixed distance of 10 cm, observing detection response and threshold triggering behavior. As no quantitative gas concentration reference instrument was available, MQ-2 results are reported in terms of detection reliability and response time rather than absolute concentration values.

The DHT22 sensor test results showed an average temperature reading of 24.71°C against a reference value of 24.49°C, yielding an average error of 0.22°C or 99.1% accuracy. For humidity, the average sensor reading was 63.40% RH compared to a reference of 62.81% RH, with an average error of 0.59% RH. These values remain within the tolerance limits of the DHT22 specification (±0.5°C for temperature and ±2% RH for humidity under normal conditions). The GY-MAX4466 sensor showed an average reading deviation of ±1.3 dB against the reference sound level meter. The MQ-2 sensor successfully detected smoke in every test trial with no false negatives, with an average detection response time of 1.8 seconds after smoke exposure. The energy efficiency of the ESP32 in handling multi-sensor real-time data acquisition at this level of accuracy has been confirmed in previous studies (Dzahir & Chia, 2023; Muslem R, 2021; Yuniarto et al., 2023). A summary of the DHT22 sensor accuracy test results is presented in Table 1.

Table 1. Sensor Accuracy Test Results DHT22

No.	Sensor Temperature (°C)	Temperature Ref. (°C)	Sensor Humidity (%)	Humidity Ref. (%)
1	24.5	24.3	63.2	62.5
2	24.6	24.4	63.5	62.8
3	24.8	24.5	63.1	62.6
4	24.7	24.5	63.8	63.1
5	24.9	24.6	63.4	62.9

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No.	Sensor Temperature (°C)	Temperature Ref. (°C)	Sensor Humidity (%)	Humidity Ref. (%)
6	24.6	24.4	63.2	62.7
7	24.8	24.6	63.6	63.0
8	24.7	24.5	63.3	62.8
9	24.8	24.6	63.5	62.9
10	24.7	24.5	63.4	62.8
Average	**24.71**	**24.49**	**63.40**	**62.81**

ESP-NOW Packet Loss and Latency Testing

ESP-NOW protocol performance testing was conducted by transmitting 100 data packets from the sensor node to the gateway node under three different distance conditions: 5 meters, 10 meters, and 25 meters with one layer of concrete wall as an obstacle. The measured parameters were the number of successfully received packets (packet loss) and transmission delay (latency) in milliseconds (ms).

Test results showed that at a distance of 5 meters, the system successfully received 100 out of 100 packets (0% packet loss) with an average latency of 12.4 ms. At 10 meters, packet loss was recorded at 1% with an average latency of 18.7 ms. At 25 meters with one concrete wall obstacle, packet loss was 5% with an average latency of 24.3 ms. All results remain within acceptable performance boundaries for a real-time monitoring system, where a packet loss rate of ≤5% is considered acceptable for real-time IoT monitoring applications (Surbakti, Ginting, Romadhona, Ginting, & Ni'amah, 2024; Wedyanti & Wagyana, 2025).

A summary of the packet loss and latency test results is presented in Table 2.

Table 2. Packet Loss and Latency Testing of ESP-NOW Protocol

Condition	Packets Sent	Packets Received	Packet Loss (%)	Latency (ms)
Distance 5m (Line of Sight / No Obstacle)	100	100	0%	12.4
Distance 10m (Line of Sight / No Obstacle)	100	99	1%	18.7
Distance 25m (1 concrete wall)	100	95	5%	24.3

Threshold and Abnormal Condition Testing

Threshold testing was conducted to verify the system's ability to distinguish between normal and abnormal conditions. The thresholds applied were: temperature > 25°C categorized as a warning condition, humidity > 75% RH considered to exceed the safe limit for electronic equipment, and smoke detected by the MQ-2 sensor at an ADC value > 400 immediately triggering a danger status. The humidity threshold of 75% RH was determined based on general guidelines for electronic equipment operation, which recommend maintaining relative humidity below this level to prevent condensation and corrosion on electronic components. The sound parameter from the GY-MAX4466 sensor was monitored continuously as an indicator of machine operational condition and was excluded from threshold-based triggering due to the highly variable nature of ambient sound levels in the transmitter room (Wiranto & Nurwarsito, 2022).

Testing was performed under controlled conditions to ensure the validity of threshold detection results. For temperature testing, a heater was used to gradually raise the temperature above 25°C. For humidity, a humidifier was used until the level exceeded 75% RH. For smoke testing, a lit match was brought close to the MQ-2 sensor at a distance of 10 cm. The threshold test results are presented in Table 3.

Table 3. Results of Threshold Testing and Abnormal Conditions

Parameter	Threshold	Test Value	Status	Notific ation
Temperature (DHT22)	> 25°C	26.3°C	Alert	Active
Humidity (DHT22)	> 75% RH	77.8% RH	Alert	Active
Smoke (MQ-2)	ADC > 400	ADC = 612	DANGER	Active
Sound (GY-MAX4466)	Monitoring	68.4 dB	NORMAL	Inactiv e

Early Warning System Response Time Testing

Response time testing aimed to measure the time elapsed from when a sensor detects an abnormal condition to when the warning notification appears on the web interface and the buzzer sounds. Testing was conducted 10 times for each parameter. Response time was measured using automatic timestamps at two points: when the sensor value first exceeded the threshold, and

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when the notification was received on the web dashboard.

Results showed an average response time of 1.14 seconds for abnormal temperature conditions, 1.21 seconds for abnormal humidity, and 1.32 seconds for smoke detection. These values fall well below the general IoT-based EWS response time benchmark of 3 seconds, consistent with findings from similar early warning systems using comparable microcontroller and communication architecture (Fasya et al., 2024; Pakage & Rianto, 2025; Wikantama, Bahalwan, & Akmal, 2024). Detailed test results are presented in Table 4.

Table 4. Sensor Response Time and Data Update Testing Results

Attempt	Temperature (seconds)	Humidity (seconds)	Smoke (seconds)
1	1.12	1.19	1.35
2	1.15	1.22	1.28
3	1.11	1.20	1.31
4	1.14	1.23	1.34
5	1.16	1.21	1.30
6	1.13	1.19	1.33
7	1.15	1.22	1.29
8	1.14	1.20	1.35
9	1.13	1.21	1.31
10	1.15	1.22	1.30
Average	**1.14**	**1.21**	**1.32**

Web Monitoring Dashboard Display

The web monitoring dashboard was designed as a centralized interface for TMB technicians to monitor the transmitter room conditions in real-time. The dashboard was built using a web-based framework directly integrated with the MQTT broker, enabling asynchronous data updates without requiring a page refresh (Eni Dwi Wardihani et al., 2024; Nandika & Amrina, 2021).

The dashboard displays several key components: (1) a real-time status card showing the latest values from each sensor, with green indicators for normal conditions and red for warnings or hazards; (2) a historical graph displaying the trend of sensor values over time; (3) an alert log panel that records any events along with their timestamps; and (4) a node connection status indicator that indicates whether the sensor node is actively transmitting data.

The physical parameter monitoring system transmits real-time room condition data. Data updates to the dashboard only occur when a sensor value changes. If no change occurs within 10 seconds, the system will not record new data. However, if a hazardous condition is detected, data will be recorded automatically without waiting for that time interval, so that TMB technicians can still obtain fast and accurate information without having to be on-site. The integration of real-time alerts with predictive analytics in web-based dashboards has been identified as a key feature for enhancing the reliability of IoT environmental monitoring systems(M. Sultan, 2025).

In terms of communication performance, the ESP-NOW protocol demonstrated an average latency ranging from 12.4 ms to 24.3 ms depending on distance and obstacle conditions, with a packet loss rate of 0% at 5m line-of-sight, 1% at 10m, and 5% at 25m through a concrete wall across 100 transmission trials per condition. These results confirm that the ESP-NOW protocol is capable of supporting reliable real-time local data transmission between nodes, which is a critical requirement for timely hazard detection and early warning notification in the transmitter room monitoring system.

CONCLUSIONS AND SUGGESTIONS

Conclusion

This research successfully designed and built an IoT-based monitoring and early warning system for the transmitter room of LPP RRI Manado. The developed system is capable of monitoring four environmental parameters in real-time using the DHT22, GY-MAX4466, and MQ-2 sensors integrated with the ESP32 microcontroller.

The hybrid protocol architecture combining ESP-NOW for inter-building data transmission and MQTT for web dashboard integration proved to be effective and efficient. The early warning system successfully delivered notifications through the buzzer and web interface within an average of 1.2 seconds upon detection of abnormal conditions. Accordingly, this system can enhance operational reliability and minimize the risk of fatal damage to LPP RRI Manado's broadcast infrastructure.

Nevertheless, several limitations of the current implementation should be acknowledged. First, the ESP-NOW communication performance may degrade in environments with dense physical obstructions or high radio frequency interference, as evidenced by the 5% packet loss observed at 25m through a concrete wall. Second, the MQ-2 sensor lacks quantitative gas concentration measurement capability, limiting its use to qualitative smoke detection only. Third, the system currently relies on a stable Wi-Fi internet connection for MQTT-based dashboard updates; any network disruption may delay or interrupt data delivery to remote users. These limitations present opportunities for future research to explore more robust communication protocols, higher-precision gas sensors, and offline-capable data logging mechanisms.

Suggestion

Several recommendations for future research development include: (1) Adding a camera sensor for real-time visual monitoring of the transmitter room; (2) Integrating mobile application-based notifications so that TMB technicians can receive alerts anywhere; (3) Developing a long-term data logging feature for environmental trend analysis; (4) Implementing machine learning for anomaly prediction before critical conditions occur.

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