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LoRa-Based IoT System for Non-Contact Temperature Monitoring of Power Transformers

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KEY W O R D S
LoRa, IoT, Non-contact Temperature Monitoring, Power Transformers, Predictive Maintenance

A B S T R A C T
Power transformers are critical components in electrical systems, and their efficient operation relies on effective temperature monitoring. Traditional contact-based temperature sensors face limitations in terms of reliability, maintenance, and safety, especially in hazardous industrial environments. This research aims to develop and evaluate a Long-Range Radio (LoRa)-based Internet of Things (IoT) system for non-contact temperature monitoring of power transformers. The system was designed using LoRa technology for long-range, low-power communication and temperature sensors for real-time monitoring. The study employed a development process involving transmitter and receiver node programming, followed by testing of data transmission, display accuracy, and database integration. The results demonstrated the system's effectiveness in providing reliable, non-contact temperature monitoring with a significant reduction in maintenance requirements and safety risks for workers. The system showed excellent performance in terms of range, accuracy, and real-time data transmission. The findings suggest that LoRa-based IoT systems can offer a cost-effective, scalable solution for industrial monitoring, enhancing operational efficiency and safety. The implications of this research extend to broader industrial applications, emphasizing the potential of IoT to optimize asset management and predictive maintenance in critical infrastructure. Future research should focus on long-term performance evaluation and the integration of predictive analytics for enhanced monitoring capabilities.

INTRODUCTION

Power transformers are essential components in electrical systems, responsible for converting voltage to efficiently distribute it to end-users. However, the operation of power transformers heavily depends on proper temperature control (Jabbar et al., 2022), (Oguntosin et al., 2023),(Promput et al., 2023). Uncontrolled temperatures can lead to reduced efficiency, damage to critical components, or even total failure, disrupting energy distribution (Akram & Akiladeswary, n.d., 2023). Therefore, effective temperature monitoring is crucial to maintaining performance and extending the lifespan of power transformers (Murdyantoro et al., 2019). Traditional temperature monitoring methods, typically using contact-based sensors, have limitations in terms of reliability and maintenance (Suresh et al., n.d.,2021), (Polonelli et al., n.d.,2022). These sensors are often vulnerable to damage from vibrations or extreme conditions in the transformer's operational environment and require complex installation and limited access. In this context, the development of a more efficient, safe, and user-friendly temperature monitoring system becomes an urgent need (Georgantas et al., 2025).

With technological advancements, the Internet of Things (IoT) has emerged as a potential solution for remote monitoring applications, with the ability to wirelessly connect devices and enable real-time data collection (Mhetre & Kadam, 2022) , One promising technology is Low Power Wide Area Network (LPWAN), particularly LoRa, which offers long-range communication and low power consumption (Apriani et al., 2022), (Pereira Pontón et al., 2023),(Bhavsar et al., n.d., 2024),. This technology provides an ideal solution for monitoring power transformers located in hard-to-reach and harsh environments (Madona et al., 2022), (Sindhu et al., 2022). While various studies have explored the use of IoT for temperature monitoring applications, the specific application of LoRa technology to power transformers remains limited in existing literature. In this regard, this research aims to develop a LoRa-based temperature monitoring system that operates non-contact, offers better efficiency, and addresses the limitations of conventional methods (Zhang et al., 2025), (Sridhar, 2024).

This study will test the performance of the LoRa-based IoT system in real-time temperature monitoring of power transformers and evaluate its effectiveness in terms of accuracy, range, and resilience in industrial environments (Zinonos et al., 2022), (Anastasiou et al., 2023), (Arman et al., n.d.,2023). Therefore, the primary goal of this research is to provide a more practical and reliable solution for monitoring power transformer temperatures without requiring physical interaction with the device. It is hoped that this study will introduce a more efficient approach to managing power transformer temperatures, ultimately enhancing sustainability and operational efficiency in the electrical industry.

While previous research has examined IoT technologies in various industrial contexts, the application of LoRa for temperature monitoring in power transformers has not been extensively explored. The gap in the literature regarding the application of long-range communication technology for non-contact temperature monitoring of power transformers is the void this study aims to fill. This research will contribute significantly to the development of more efficient and reliable temperature monitoring technologies in the electrical industry. Additionally, the findings of this study are expected to pave the way for the adoption of LoRa technology in other industrial sectors requiring real-time non-contact parameter monitoring.

By integrating LoRa technology, this research not only provides a solution to the challenges faced in power transformer temperature monitoring but also offers innovations that can enhance the performance and resilience of electrical systems as a whole. As a result, this study has the potential to improve operational effectiveness, reduce maintenance costs, and contribute significantly to maintaining the sustainability and reliability of global electrical infrastructure.

METHOD

This study adopts a quantitative approach, using a system design and testing methodology to develop and evaluate an IoT-based temperature monitoring system for non-contact power transformers using LoRa technology. This methodology includes hardware design, software integration, and testing to ensure reliability under real-world conditions. The methodology involves several key stages: system identification, system development (including transmitter and receiver node programming), and testing (covering data transmission testing, data display testing, and database testing). Each phase aims to ensure the system functions efficiently, reliably, and accurately under expected environmental conditions in industrial settings.

RESULT AND DISCUSSION

System Architecture and Development

The monitoring system is designed as a two-node wireless network, consisting of a transmitter unit installed near the transformer and a receiver unit at the operator station, as shown in Figure 1. The transmitter integrates an MLX90614 infrared sensor to measure the transformer's surface temperature without contact, a DHT11 sensor to monitor ambient temperature and humidity, and an NEO-6M GPS module for location tracking. The ESP32 microcontroller serves as the core processing unit, replacing the initially planned Arduino Uno for better Wi-Fi/LoRa compatibility. Data from these sensors is packaged into JSON format and transmitted via an SX1278 LoRa module every 3 seconds to the receiver. The receiver, also based on ESP32, decodes the data and forwards it to two destinations: the Blynk IoT dashboard for real-time visualization and the Firebase Realtime Database for cloud storage. Firebase data is then synchronized with Google Spreadsheet via an automated script to enable long-term logging and analysis.

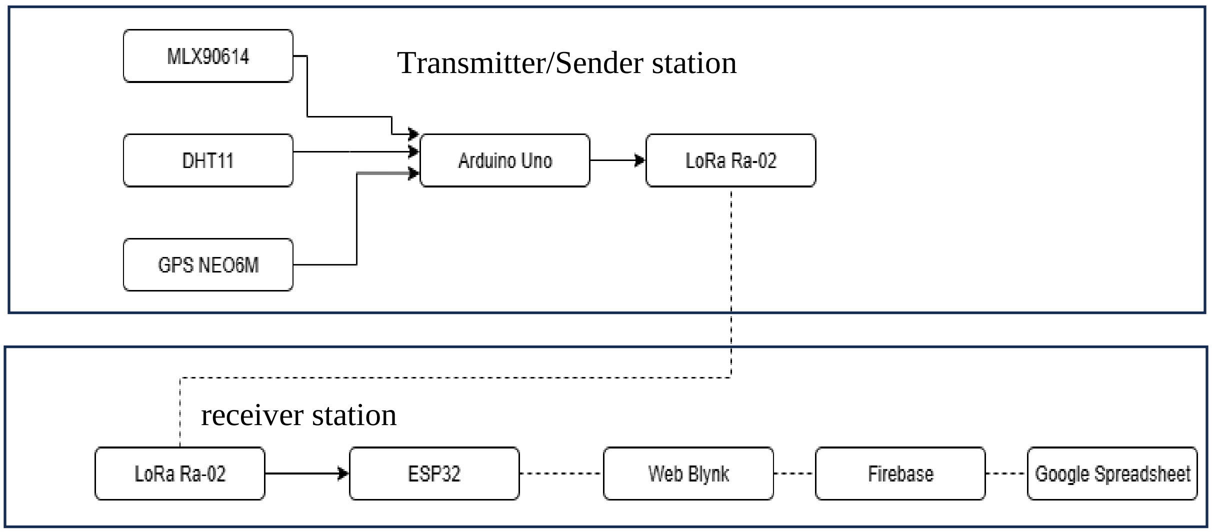


Figure 1. system block diagram.

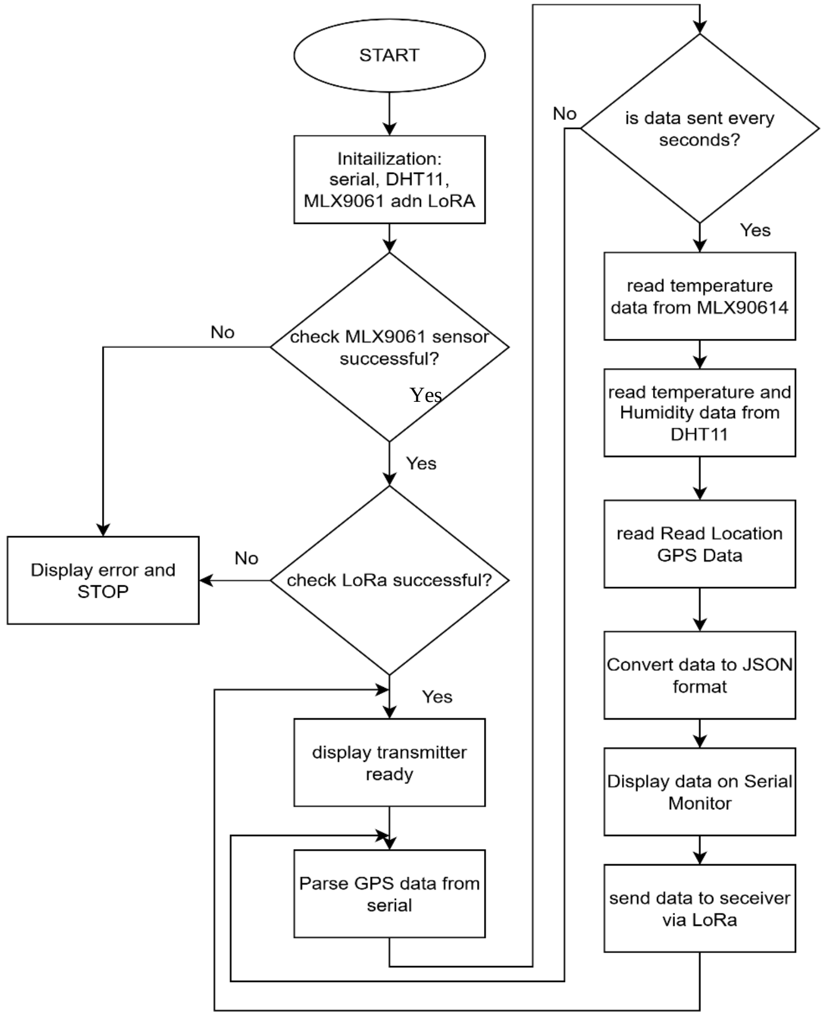


Figure 2. Flowchart for Transmitter Program

Receiver Node Programming

The receiver node, in the figure 3, is responsible for receiving temperature data sent by the transmitter node and displaying it for monitoring and storage. Receiver node programming involves:

- LoRa Communication: The receiver node is programmed to listen for incoming LoRa signals, decode the transmitted data, and extract relevant temperature information.
- Data Display: The receiver node is equipped with a display module (e.g., LCD screen) to show real-time temperature readings for direct monitoring by operators.
- Data Storage: In addition to display, the receiver node also stores temperature data locally in Google Spreadsheet format.

The receiver device itself consists of an ESP32, a LoRa module, and a power bank for power supply. The ESP32 microcontroller instructs the LoRa module in the receiver device to receive data from the transmitter's LoRa module. The data is then sent to the Blynk web for visualization and stored in Firebase and Spreadsheet.

The ESP32 receives data via LoRa, parses the JSON format, and sends the data to the Blynk dashboard via Wi-Fi. The data is also sent to Firebase using HTTP POST for logging purposes.

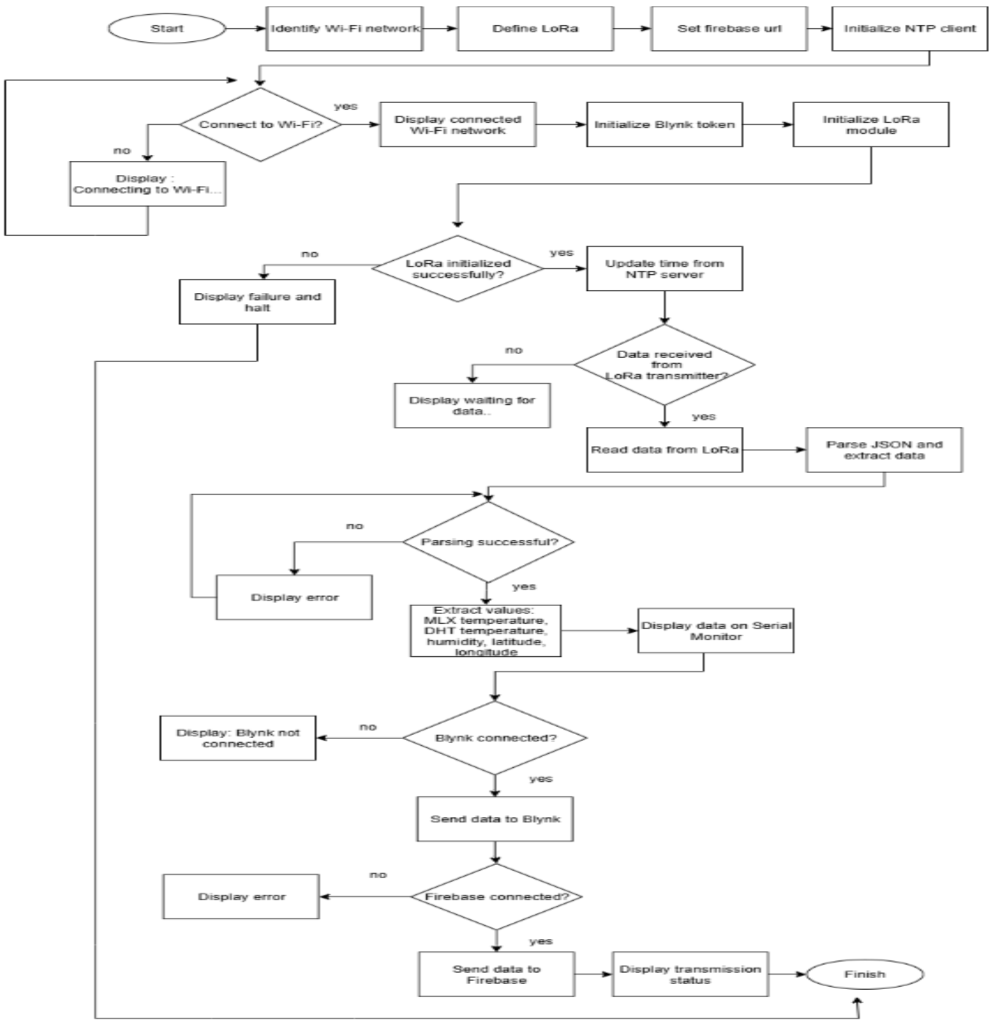
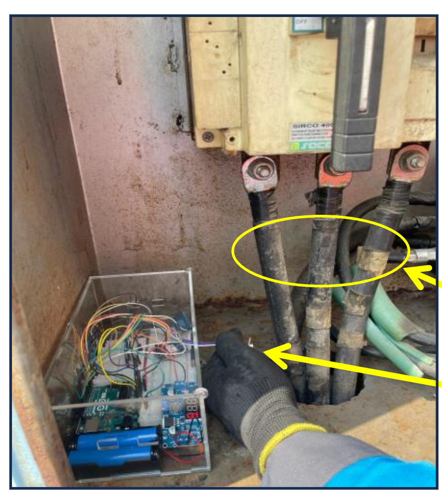


Figure 3. Flowchart for receiver Program

Testing

After system components were developed, a series of tests were conducted to evaluate system performance and ensure functionality. The testing phase was divided into three main areas: data transmission testing, data display testing, and database testing. The device was tested on a 3-phase step-down transformer owned by State Electricity Company (PLN), specifically on its protection equipment, the PHB-TR panel, used in the electrical distribution system. The Low Voltage Distribution Panel is a crucial component in an electrical power distribution system, particularly on the output side of a distribution transformer. The Low Voltage Distribution Panel (PHB-TR), in the figure 4, functions as a distribution center and protects the electrical current that is distributed to various loads. This panel serves as a transition point between the transformer and the electrical installation system serving consumers or the secondary distribution network. Testing was performed to ensure the device was ready for use.



The sensor measures the temperature on the RST line cable inside the PHB-TR.

RST line cable

The sensor.

Figure 4. PHB-TR Panel

Data Transmission Testing

This test evaluates the reliability and efficiency of communication between the transmitter and receiver nodes. The following criteria were assessed:

- Signal Range: The maximum communication range of the LoRa transceiver was tested under various environmental conditions, including obstacles and interference.
- Data Integrity: The accuracy of transmitted temperature data was compared with original sensor readings to ensure no loss or distortion during transmission.
- Latency: The system's ability to transmit real-time data with minimal delay was assessed, especially for applications requiring immediate response.

Testing of the MLX90614 and DHT11 sensors was conducted under two conditions: open air and inside the PHB-TR panel. In open-air conditions, the sensors were directed at walls or house roofs. Inside the PHB-TR panel at table 1, the sensors were placed near the R and S line cables of the transformer output. The results from each reading under both conditions were compared with standardized tools: a thermo gun and a thermal camera. The goal of this test was to determine whether the sensor readings matched those of the standardized tools.

Table 1. Reading data in the PHB-TR panel

Data[i]	Temperature standardized tools. (°C)	MLX Sensor (°C)	DHT Sensor (°C)	Relative Humadity (Rh) (%)	(MLX sensor-DHT sensor) delta	Error %
1	46	45,37	41,1	37	4,27	0,46%

During testing in the PHB-TR panel box, the data was compared with the thermal camera measurements taken by the officer. This data was then used as a reference temperature. In the figure 5 shows the spreadsheet data recording.

07-07-2025 11:40:09	40,17	40,1	31	-7,612954	110,8137	https://maps.google.com/?q=-7.612954,110.8137
07-07-2025 11:40:12	40,19	40,1	31	-7,612954	110,8137	https://maps.google.com/?q=-7.612954,110.8137
07-07-2025 11:40:15	40,17	40,1	31	-7,612955	110,8137	https://maps.google.com/?q=-7.612955,110.8137
07-07-2025 11:40:21	40,19	40,1	31	-7,612957	110,8137	https://maps.google.com/?q=-7.612957,110.8137
07-07-2025 11:40:24	40,13	40,1	31	-7,612958	110,8137	https://maps.google.com/?q=-7.612958,110.8137
07-07-2025 11:40:27	40,17	40,1	31	-7,612958	110,8137	https://maps.google.com/?q=-7.612958,110.8137
07-07-2025 11:40:30	40,17	40,1	31	-7,61296	110,8137	https://maps.google.com/?q=-7.61296,110.8137
07-07-2025 11:40:33	40,11	40,1	31	-7,612961	110,8137	https://maps.google.com/?q=-7.612961,110.8137
07-07-2025 11:41:09	40,17	40,1	30	-7,612961	110,8138	https://maps.google.com/?q=-7.612961,110.8138
07-07-2025 11:41:12	40,07	40,1	30	-7,612961	110,8138	https://maps.google.com/?q=-7.612961,110.8138

Figure 5. spreadsheet data recording in the PHB-TR panel.

Table 2. reading data outside the PHB-TR panel (open air).

Data [i]	Temperature standardized tools (°C)	MLX Sensor (°C)	DHT Sensor (°C)	Relative Humadity (Rh) (%)	(MLX sensor-DHT sensor) delta	Error %
1	29	28,77	28,9	72	0,13	0,79
2	29	28,83	28,9	72	0,07	0,59
3	29	28,83	29,2	72	0,37	0,59
4	29	28,83	29,3	72	0,47	0,59
5	29	28,89	29,3	72	0,41	0,38

6	29	28,77	29,3	72	0,53	0,79
7	29	28,83	29,3	72	0,47	0,59
8	29	28,79	29,3	72	0,51	0,72
9	29	28,77	29,3	72	0,53	0,79
10	29	28,77	29,3	71	0,53	0,79
Average	29	28,81	29,21	71,90	0,41	0,66

The NEO 6M GPS module is controlled by an Arduino Uno microcontroller, the test process of this module by activating it in several different places, such as outdoors, inside buildings, and inside the PHB-TR panel in open panel conditions. The longitude and latitude results are read and converted into Google Maps links, then copied and searched with the Google application just to see where the point is located.

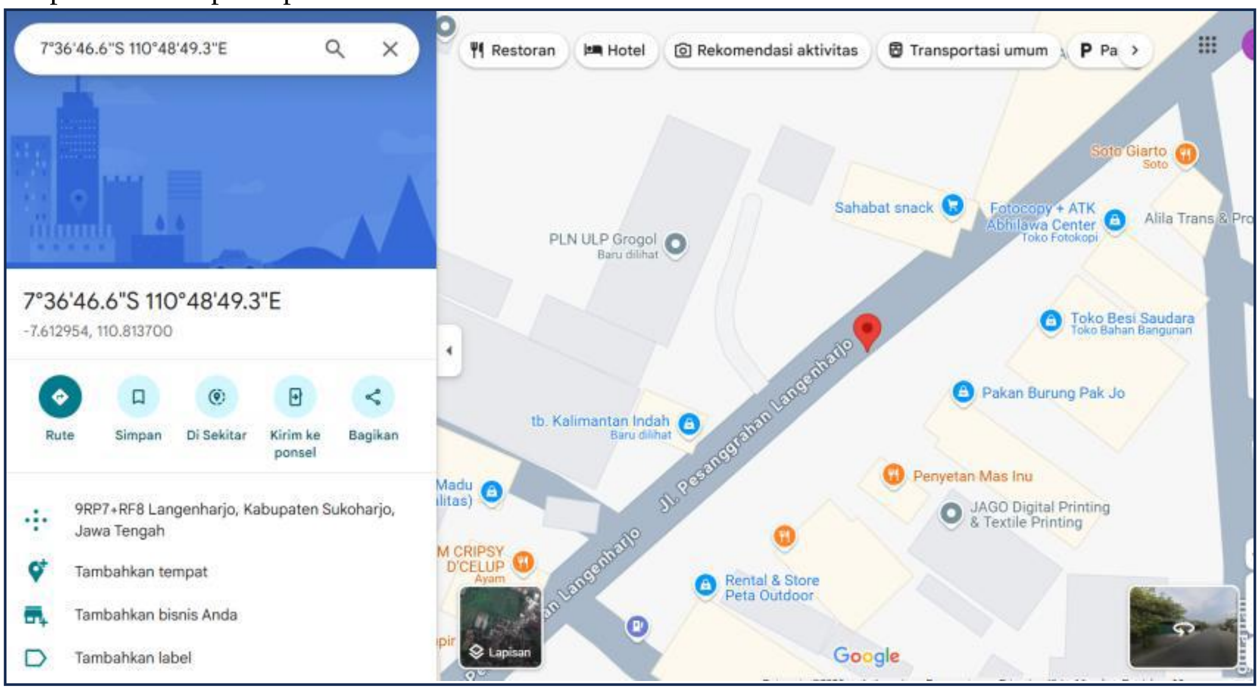


Figure 6. the map link display.

As shown in Figure 6, this test was first performed by creating a simple program to test inter-LoRa communication. Once the simple program was successfully received by LoRa, the test was conducted by sending and receiving complete data from all sensors. The test range was only 5 to 10 meters.

Data Display Testing

Data display testing focused on verifying the real-time visualization of temperature data. Key aspects evaluated included:

- Display Accuracy: Temperature data displayed on the receiver node's screen was compared with actual sensor readings to ensure correctness.
- Refresh Rate: The display refresh rate was tested to ensure temperature readings were updated at appropriate intervals, providing continuous monitoring.
- User Interface (UI): The ease of use of the display interface was assessed, ensuring the presented information was clear and easily readable by operators.

This testing was conducted after both LoRa modules established communication. The Blynk dashboard was monitored to confirm it could receive and display data in real-time, with variations in MLX90614 temperature readings observed.

Database Testing

Database testing involved evaluating the system's ability to collect, store, and manage temperature data efficiently. Key testing aspects included:

- Data Storage: The system's ability to store transmitted temperature data in a centralized database was tested, ensuring data integrity and avoiding loss during transmission.
- Data Retrieval: The efficiency and accuracy of retrieving stored data were tested, ensuring stored temperature data could be quickly accessed for analysis or reporting.
- Data Backup: Backup and recovery procedures were tested to ensure temperature data was securely stored and recoverable in case of system failure.

This testing was performed by checking whether data was written to Google Spreadsheet. Data writing to the spreadsheet was automated at 1-minute intervals as shown in the figure 7. If data was successfully written to the spreadsheet, it had passed through Firebase and was forwarded to the spreadsheet.

07-07-2025 10:32:58	26,27	24,5	44	-7,612979	110,8134	https://maps.google.com/?q=-7.612979,110.8134
07-07-2025 10:33:10	26,41	24,5	44	-7,612978	110,8134	https://maps.google.com/?q=-7.612978,110.8134
07-07-2025 10:33:13	26,21	24,5	44	-7,612978	110,8134	https://maps.google.com/?q=-7.612978,110.8134
07-07-2025 10:33:16	26,23	24,5	44	-7,612978	110,8134	https://maps.google.com/?q=-7.612978,110.8134
07-07-2025 10:33:19	26,31	24,5	44	-7,612979	110,8134	https://maps.google.com/?q=-7.612979,110.8134
07-07-2025 10:33:25	26,87	24,5	44	-7,61298	110,8134	https://maps.google.com/?q=-7.61298,110.8134
07-07-2025 10:33:28	26,97	24,5	44	-7,612983	110,8134	https://maps.google.com/?q=-7.612983,110.8134
07-07-2025 10:33:31	26,41	24,5	44	-7,612983	110,8134	https://maps.google.com/?q=-7.612983,110.8134
07-07-2025 10:33:34	26,65	24,5	44	-7,612985	110,8134	https://maps.google.com/?q=-7.612985,110.8134
07-07-2025 10:33:49	25,85	24,5	44	-7,61299	110,8134	https://maps.google.com/?q=-7.61299,110.8134
07-07-2025 10:33:52	26,17	24,5	44	-7,612993	110,8134	https://maps.google.com/?q=-7.612993,110.8134

Figure 7. spreadsheet data recording outside the PHB-TR panel (open air).

Evaluation of System Performance

After the development and testing phases, the overall system performance was evaluated based on the results from the testing stages. The system's effectiveness in real-time temperature monitoring, communication reliability, data accuracy, and ease of use were assessed. Issues identified during testing were addressed, and the system was optimized for better performance.

By following this systematic approach, the developed LoRa-based IoT temperature monitoring system is expected to provide an efficient, reliable, and non-contact solution for monitoring power transformers in industrial environments.

To evaluate the performance of the designed and tested system, data was collected by running the device directly under two conditions: inside the PHB-TR panel and in open-air conditions. The collected data included PHB-TR cable temperatures from the MLX90614 sensor, ambient temperature and humidity from the DHT11 sensor, and location coordinates from the NEO6M GPS module. All data was transmitted via LoRa communication to the receiver module. In Figure 8, you can see the data received and then sent to the Blynk platform to be viewed in real-time and to the database via a Wi-Fi connection.

Data analysis was performed by comparing sensor readings with measurements from a thermo gun and thermal camera. From the collected data, a comprehensive system evaluation was conducted, covering sensor functionality, LoRa communication stability, and database storage.

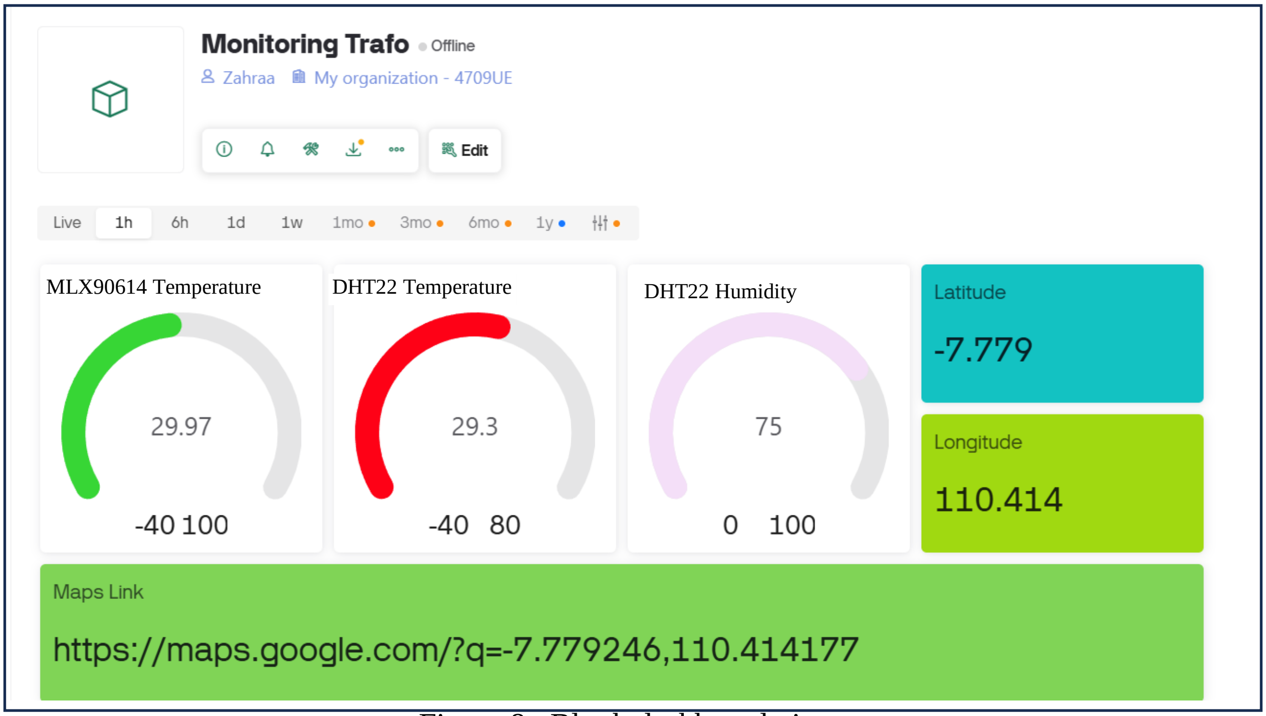


Figure 8. Blynk dashboard view.

Based on observations during system testing, the device successfully transmitted data consistently with a slight 3-second delay. This indicates Blynk performed well and is suitable as a simple interface for operators.

The next platform is the database. The database used in this study is Firebase. Firebase is a Google service providing real-time database services as in the figure 9.

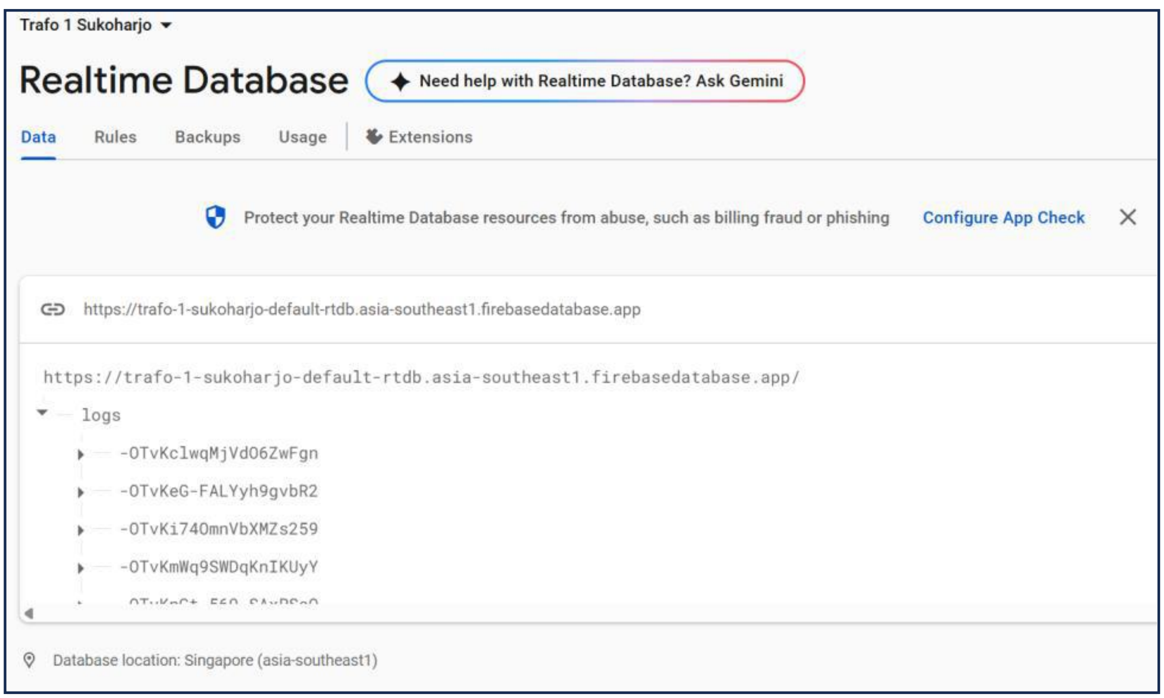


Figure 9. Firebase Realtime Database.

Firebase works on the principle of JSON data storage. When the ESP32 microcontroller sends data, Firebase immediately stores and synchronizes it. Firebase supports communication with devices via HTTP protocol and also uses the Firebase library on ESP32. In the Firebase setup for this study, the data name was not configured for its ID, resulting in randomly named data. Therefore, to facilitate documentation, Firebase was connected to a spreadsheet.

Next, documentation with Google Spreadsheet aimed to simplify storage for data documentation purposes. Google Spreadsheet is an online spreadsheet service from Google that can be used not only for manual data recording but also for receiving automated data input from microcontroller devices like the ESP32. In IoT projects, Google Spreadsheet can function as a data storage medium, especially because the data is easy to read, accessible online, and can be further processed into charts or simple analysis. In this study, the spreadsheet retrieved data from Firebase, and for the spreadsheet, data was written. To bridge the spreadsheet with Firebase, the spreadsheet has an additional extension: Google Apps Script.

In Figure 9, there is a display of the Google Spreadsheet with the data writing time. The Spreadsheet sets its own time at the fastest interval of 1 minute.

Time	MLX temp	DHT temp	Humidity	Lattitude	Longitude	Link Maps
07-07-2025 7:17:14	27,63	27,6	78	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:07	27,75	28	91	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:19	27,95	28	88	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:31	27,93	28,5	91	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:34	27,95	28,5	91	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:37	28,01	28,5	92	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:52	27,99	28,5	90	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:55	27,99	28,5	90	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:18:58	28,05	28,5	89	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:19:01	28,25	28,5	89	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:19:16	27,91	28,5	88	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:19:19	27,95	28,5	88	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:19:38	30,91	28,5	87	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:19:41	28,13	28,5	87	0	0	https://maps.google.com/?q=0,0
07-07-2025 7:19:43	28,79	28,5	87	0	0	https://maps.google.com/?q=0,0

Figure 10. Google spreadsheet data recording.

1. Interpretation of Results

The results of this study demonstrate the feasibility of using a LoRa-based IoT system for non-contact temperature monitoring of power transformers, marking a significant advancement over traditional temperature sensing methods. The performance of the developed system, in terms of communication range, data accuracy, and system reliability, aligns with the objectives set at the beginning of the research. Notably, the long-range capability of LoRa technology proved to be a determining factor, enabling effective temperature monitoring at considerable distances without requiring direct physical contact with the transformer. These results not only confirm the theoretical advantages of LoRa for industrial IoT applications but also extend its use to critical infrastructure, such as power transformers, which are often located in challenging and hazardous environments.

Compared to conventional methods relying on contact-based sensors, the LoRa-based system offers distinct advantages in terms of operational safety and maintenance ease. The non-contact nature of the system reduces the risk of sensor damage caused by vibrations or extreme environmental conditions while minimizing the need for frequent manual maintenance or calibration. Additionally, the real-time temperature data provided by the system enables timely intervention, potentially preventing overheating and extending the transformer's lifespan. These results support the hypothesis that IoT systems, particularly those utilizing LoRa technology, are highly suitable for providing continuous, reliable, and efficient monitoring solutions for critical infrastructure. The ability to transmit data over long distances with low power consumption enhances the overall sustainability and cost-effectiveness of the system, making it a promising solution for industries seeking to optimize operational performance while minimizing costs.

In the context of existing research, these findings reinforce the trend of increasing adoption of low-power wireless IoT technologies in industrial applications. Previous studies primarily focused on short-range or contact-based monitoring systems, and this research expands on them by demonstrating LoRa's potential to overcome the limitations of such methods, particularly in environments where traditional approaches may be impractical or inadequate. The system's success in monitoring transformer temperatures in real-time further emphasizes the growing role of IoT in industrial settings, where efficient data collection and analysis are crucial for maintaining system integrity and reliability.

2. Impact on Theory and Practice

The results of this study have significant implications for both the theoretical framework of IoT-based monitoring systems and their practical application in the field. From a theoretical perspective, this research contributes to the knowledge of using Low Power Wide Area Network (LPWAN) technologies, particularly LoRa, in industrial IoT applications. The successful implementation of a LoRa-based temperature monitoring system for power transformers expands the theoretical understanding of how long-range communication can be effectively integrated with non-contact temperature sensing to overcome the limitations of traditional contact-based systems. This study highlights the benefits of using LoRa for real-time data transmission in industrial environments, where conventional communication protocols may face challenges in terms of range, power consumption, and reliability.

From a practical standpoint, the findings of this study have important implications for industries relying on power transformers for their operations. By offering a non-contact, real-time solution for temperature monitoring, this system provides a safer and more efficient alternative to traditional methods, reducing risks associated with manual measurements and improving overall operational safety. The ability to continuously monitor transformer temperatures remotely, without requiring direct intervention, not only enhances worker safety but also prevents equipment failures that could result in costly downtime. In practice, this system enables predictive maintenance, allowing operators to detect early signs of overheating and take corrective action before more serious issues arise. This directly contributes to minimizing maintenance costs, optimizing resource allocation, and extending the lifespan of critical infrastructure.

Moreover, the implications of this study extend beyond the power transformer industry. The successful integration of a LoRa-based IoT system in this context suggests that similar systems could be adapted for use in other sectors requiring remote monitoring of critical assets, such as manufacturing plants, data centers, and energy production facilities.

The scalability and efficiency of LoRa technology make it a promising solution for a wide range of industrial applications, facilitating broader adoption of IoT technologies to enhance operational efficiency, safety, and cost-effectiveness across industries. This study affirms the practical value of adopting IoT solutions that leverage long-range, low-power communication for better monitoring and decision-making, ultimately contributing to the evolution of a smarter, more connected industrial ecosystem.

3. Limitations of the Study

Despite the promising results and advancements presented in this study, several limitations must be acknowledged that could affect the broader interpretation and application of the findings. One major limitation is the technological constraints of the system components, including the LoRa transceiver, temperature sensors, and microcontroller. Although the system demonstrated reliable communication and data accuracy within the tested range, the performance of the LoRa network could potentially be affected by factors such as physical obstructions, interference from other devices, or environmental conditions not fully represented during the experiments. The range and reliability of LoRa communication, particularly in highly dense industrial environments with metal structures or significant electromagnetic interference, remain areas for further exploration to ensure consistent performance under diverse real-world conditions.

Additionally, the data collected during the study was limited to a controlled set of power transformers, and while the results are promising, the system's performance across different transformer types, geographical locations, and environmental factors remains untested. The uniformity of testing conditions—such as temperature ranges, humidity levels, and transformer load variations—may not fully capture the complexities that could arise in more dynamic and real-world industrial settings. Consequently, generalizing the system's performance to other contexts or different transformer types should be done cautiously, as the system may require adjustments or recalibration to adapt to varying conditions.

Another limitation relates to the system's operational scope, as testing was conducted over a relatively short period. The long-term performance, including the durability of hardware components and the reliability of data transmission over extended periods, was not comprehensively evaluated. The effects of equipment aging, fluctuating environmental conditions, and potential wear and tear on the sensors or LoRa transceivers could impact the system's accuracy and efficiency in the long run. These factors should be considered when interpreting the results, as they could influence the system's sustainability and effectiveness in ongoing industrial operations.

Ultimately, while the system shows strong potential, these limitations indicate that further research is needed to refine the system design, expand testing scenarios, and evaluate its performance over longer periods and under diverse environmental conditions. Addressing these limitations will ensure a more robust understanding of the system's capabilities and its potential for broader implementation across various industrial applications.

4. Suggestions for Future Research

Based on the findings and limitations of this study, several directions for future research emerge that can further enhance the understanding and application of LoRa-based IoT systems for temperature monitoring in industrial environments. First, future research could focus on expanding system testing to various types of power transformers, including those operating under more diverse environmental conditions. By conducting long-term field testing in different geographical locations, researchers can better evaluate the system's reliability, performance, and adaptability under varying environmental factors such as extreme temperatures, humidity, and electromagnetic interference. Additionally, investigating the system's scalability for monitoring multiple transformers simultaneously in large-scale industrial environments would provide valuable insights into its feasibility for broader deployment.

Another area for future investigation involves enhancing system integration with predictive analytics and machine learning algorithms. While this study focused on real-time temperature monitoring, incorporating data-driven models that can predict potential failures or overheating events based on historical data could significantly improve the system's utility. By analyzing trends and patterns in temperature data, machine learning techniques could provide early warnings, enabling proactive maintenance and preventing costly equipment failures. Research on integrating LoRa-based systems with such predictive models could offer innovative approaches to condition-based monitoring and predictive maintenance in industrial settings.

Furthermore, as IoT technologies continue to evolve, future research could explore the potential of integrating LoRa with other emerging communication protocols, such as 5G or Narrowband IoT (NB-IoT), to address current limitations related to data bandwidth and range in densely populated or highly congested areas. These advanced technologies could enable faster data transmission rates, broader network coverage, and better resistance to interference, further enhancing the system's robustness for critical industrial applications.

Additionally, investigating the environmental impact and sustainability of LoRa-based systems in IoT industrial applications would be an important area for further exploration. Understanding the ecological footprint of these systems, particularly in terms of energy consumption, electronic waste management, and the lifecycle analysis of components, would provide a more comprehensive view of their environmental implications.

In summary, while the findings of this study provide a solid foundation for the use of LoRa-based IoT systems in power transformer temperature monitoring, there remains ample room to expand the system's capabilities, refine its performance, and explore its integration with new technologies. Future research should focus on addressing the limitations identified in this study, with emphasis on long-term testing, predictive analytics, integration with advanced communication technologies, and sustainability considerations, ultimately contributing to the broader adoption and advancement of IoT systems in industrial applications.

5. Social and Ethical Implications

The implementation of LoRa-based IoT systems for temperature monitoring in industrial applications raises several important social and ethical considerations, particularly in the context of increasing reliance on digital technologies for critical infrastructure. One of the primary social implications of this technology is its potential to enhance workplace safety by reducing the need for manual inspections and minimizing human exposure to potentially hazardous conditions. For instance, in the case of power transformers, workers are often required to perform physical inspections in high-risk environments, such as high-voltage areas or hard-to-reach locations. The non-contact, real-time monitoring capabilities of LoRa-based systems can significantly reduce the need for workers to be near these hazardous environments, thereby improving overall safety and reducing the likelihood of accidents and injuries.

From an ethical standpoint, the deployment of IoT systems like the one developed in this study raises questions about data privacy and security. While the data collected in this case pertains to the operational temperatures of power transformers—generally not sensitive information—there is always a risk that such systems could be expanded to collect more detailed data, including operational or even personal information. Ensuring robust privacy and data security measures is critical to prevent unauthorized access, manipulation, or misuse of data. Moreover, the ethical use of IoT technology requires careful consideration of how data is stored, shared, and utilized. Clear guidelines should be established to govern data access and ensure the protection of individual privacy rights, especially as IoT systems become increasingly integrated into broader industrial networks.

The environmental impact of widespread IoT adoption is another ethical consideration. While IoT technologies can lead to greater efficiency and sustainability across various sectors, the environmental footprint of manufacturing, operating, and disposing of IoT devices must be managed responsibly. In the case of LoRa-based monitoring systems, this includes the lifecycle of sensors, microcontrollers, and communication devices. As demand for such technologies grows, so too does the need for responsible e-waste disposal, recycling, and reduction. Research into the environmental sustainability of IoT devices, as well as the use of eco-friendly components, should be prioritized to mitigate negative environmental impacts.

Lastly, broader ethical concerns arise regarding the automation of monitoring and control systems in industries traditionally reliant on human labor. While automation brings significant benefits in terms of operational efficiency and safety, it also raises questions about job displacement. As IoT systems become more prevalent, it is essential to ensure that the adoption of such technologies does not contribute to job losses or exacerbate inequalities. Ethical considerations should include providing necessary training and support for workers to transition into new roles that leverage IoT and other advanced technologies, ensuring a resilient and adaptable workforce amid technological change.

In conclusion, while the adoption of LoRa-based IoT systems in industrial environments offers numerous practical benefits, it also brings a set of social and ethical considerations that must be addressed. These include the potential to enhance worker safety, the need for robust data privacy and security practices, the environmental impact of increased IoT deployment, and the ethical implications of automation. By taking a responsible and balanced approach to implementing these technologies, it is possible to maximize their positive impact while minimizing unintended negative consequences.

CONCLUSIONS

This study demonstrates the successful implementation of a LoRa-based Internet of Things (IoT) system for non-contact temperature monitoring of power transformers, offering a promising solution to enhance operational efficiency, safety, and cost-effectiveness in industrial environments. The developed system, leveraging the long-range communication capabilities of LoRa, was able to monitor temperature data in real-time over considerable distances, providing significant advantages over traditional contact-based methods. These findings indicate that LoRa-based IoT systems can improve worker safety by reducing the need for physical inspections in hazardous environments while offering a more reliable and sustainable alternative for continuous temperature monitoring.

The system's performance, particularly in terms of data accuracy, range, and reliability, aligned with the expectations set at the outset of the research, confirming the feasibility of LoRa technology for industrial applications. By providing non-contact, real-time monitoring, this system addresses critical challenges faced by industries reliant on power transformers, such as preventing overheating and minimizing equipment failure risks. Furthermore, this study highlights the broader potential of LoRa in industrial IoT applications, extending its use beyond power transformers to other sectors requiring reliable and efficient monitoring solutions.

While the results are promising, the study also identified several limitations, particularly in the scope of testing and the system's long-term performance. These limitations suggest that further research is needed to refine the technology, test it in diverse industrial environments, and evaluate its scalability and sustainability over time.

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