Smart Fire Detection: Leveraging IoT and Antenna Communication for Remote Hotspot Surveillance

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***Abstract*— Land and forest fires are one of the main issues that regularly happen in most tropical countries, with most trees and forestry fields. This research aims to detect fire hotspots using Internet of Things technology with an equipped Long Range (LoRa) sensor network to get environmental indicators related to fires. Integrated with the LoRa antenna for data communication, the fifth generation (5G) was used, which required real-time sending to the backend system. The system is expected to detect and monitor all parameters such as temperature, humidity, smoke, and gas emissions through the LoRa system as remote surveillance. The design has an early indicator for abnormal data detection. It sends the alert to a respective institution in charge, while the message is broadcast to the community for the information and warning system. The prototype was tested in a laboratory or in several fields to achieve and evaluate the performance of the designed system. Results show that the system has successfully detected events of fire hotspots that potentially become fire, with a fast response of less than 10 seconds. Transmission data rates are more than 90% at more than 3 kilometers efficiency in power with LoRa communication system and solar power supply. The designed system is applied for cost-effective, scalable, and real-time solutions for remote fire surveillance systems, which are managed to be used in agricultural monitoring and disaster risk. The proposed system applicable to assist government or industrial to detect and monitor forest fire specially in Indonesia region which very often experience this disaster in Sumatra and Kalimantan Island.**

Keywords—fire detection, IoT, Communication, hotspot

I. INTRODUCTION

Forest and land fires have become a recurring environmental crisis in many regions of the world, especially in tropical countries like Indonesia, Brazil, and parts of Sub-Saharan Africa. These fires not only cause severe ecological damage by destroying biodiversity and releasing vast amounts of carbon into the atmosphere, but also endanger human lives and contribute significantly to transboundary haze pollution. One of the persistent challenges in mitigating these disasters is the delayed detection of fire hotspots, especially in remote or inaccessible areas where manual monitoring is limited and conventional satellite surveillance suffers from low temporal resolution and cloud cover interference. Recent advancements in Internet of Things (IoT) technology present a promising alternative to traditional fire detection methods. Deploying sensor nodes equipped with temperature, gas, humidity, and smoke detectors, IoT-based systems can provide real-time, ground-level monitoring of fire-prone environments. These smart sensors are capable of detecting early-stage fire indicators long before flames are visible or satellite sensors can detect thermal anomalies. However, the success of such systems in remote areas hinges on the ability to transmit sensor data over long distances with minimal power consumption and infrastructure [1].

To address this challenge, this study proposes a smart fire detection system that integrates IoT sensor networks with antenna-based wireless communication technologies, such as Long Range (LoRa). These communication technologies enable low-power, long-range data transmission from sensor nodes to a centralized monitoring station, even in areas without internet or grid connectivity. The system aims to create a scalable, autonomous, and real-time surveillance network that can alert authorities to fire risks in their earliest stages. Combining the responsiveness of IoT devices with the reliability of antenna communication, this approach offers a novel solution for remote hotspot surveillance, potentially transforming how forest fires are monitored and managed [2]. The implementation of such systems can significantly reduce response times, minimize environmental and economic losses, and enhance the capacity of disaster management agencies to make data-driven decisions. This paper explores the design, deployment, and testing of the proposed system in a controlled environment, laying the groundwork for broader real-world applications in forest management, agriculture, and climate adaptation strategies.

II. LITERATURE REVIEW

Forest fire detection has traditionally relied on satellite remote sensing, which provides large-scale coverage and long-term monitoring capabilities. Notable systems such as National Aeronautics and Space Administration (NASA) Moderate-Resolution Imaging Spectroradiometer (MODIS) and The Visible Infrared Imaging Radiometer Suite (VIIRS) have been widely used to detect thermal anomalies from space. However, their effectiveness is limited by low temporal resolution, cloud cover interference, and delayed data availability [3,4]. In response to these limitations, researchers have explored ground-based technologies as complementary solutions to improve the timeliness and accuracy of fire detection, especially in high-risk or remote areas. One significant advancement is the application of IoT in environmental monitoring. IoT-based fire detection systems utilize distributed sensors to monitor temperature, humidity, smoke, and gas levels in real time [5,6]. Studies have shown that smart sensors can detect fire events in their early stages and provide instant alerts, thus improving response times and reducing fire-related damage [7-9]. Moreover, IoT systems are scalable, energy-efficient, and adaptable to diverse terrains, making them particularly suitable for forest environments. Despite the advantages of IoT, data transmission in remote areas remains a critical challenge. Many regions affected by wildfires lack reliable internet or cellular infrastructure. To overcome this, researchers have turned to antenna-based communication technologies, such as LoRa which enable low-power, wide-area communication [10-12]. LoRa, in particular, has been widely adopted for its ability to support long-range data transfer (up to 10 km) with minimal power consumption, ideal for remote and energy-constrained settings [13,14].

A growing body of work has explored the integration of IoT and LoRa for wildfire detection. For instance [15,16] developed a LoRa-based forest monitoring system that successfully transmitted sensor data from deep forest locations to central hubs. Similarly [17-19] demonstrated that LoRa networks could be integrated with mobile base stations to ensure real-time data collection in challenging environments. These studies affirm the feasibility and efficiency of combining IoT sensing with antenna-based communication to enable real-time remote surveillance. In addition to hardware design, researchers have also emphasized the importance of data processing and early warning systems. Artificial intelligence (AI) and machine learning techniques have been proposed to enhance anomaly detection and reduce false positives in fire alerts [20-22]. While this research focuses more on the hardware and communication aspects, it lays the foundation for future integration with intelligent algorithms for predictive analysis and decision support.

Existing literature supports the growing consensus that smart fire detection systems leveraging IoT and wireless communication offer significant improvements over conventional fire monitoring techniques. However, gaps remain in developing integrated, low-cost, and autonomous systems that are both technically feasible and environmentally sustainable for deployment in remote fire-prone regions. This study contributes to filling this gap by designing and testing a practical solution tailored for real-world implementation in areas with limited infrastructure and high fire vulnerability.

III. Research Methodology

This research adopts a design-based research methodology involving the development, deployment, and testing of an IoT-based fire detection system equipped with antenna communication technology. The approach is divided into four primary stages: system design, hardware implementation, field deployment, and performance evaluation [23-26].

A. System Architecture and Design

The smart fire detection system was architected to consist of distributed sensor nodes, a gateway communication module, and a central monitoring platform. Each sensor node was designed to include a microcontroller unit or ESP32, integrated with multiple sensors such as a temperature sensor DHT22, gas sensor MQ-2, smoke sensor, and flame sensor IR-based. These sensors work in combination to detect early indicators of fire presence. The sensor unit is powered by a solar panel and rechargeable battery to ensure uninterrupted operation in remote, off-grid areas. To enable long-range data transmission, each sensor node is equipped with a LoRa transceiver module SX1278. The LoRa protocol was chosen due to its low power consumption, long communication range up to 3–10 km in open areas, and robust signal performance in rural and forested environments. The gateway receives data from multiple nodes and transmits it to a central server using 5G modules as shown in fig. 1.

B. Field Deployment and Testing Environment

The prototype system was deployed in a controlled outdoor environment that simulated remote forest conditions. Several sensor nodes were distributed at varying distances (500 m, 1 km, and 2.5 km) from the central gateway to evaluate communication range and sensor accuracy. Controlled fires were simulated using heat sources and smoke generators under strict safety protocols to trigger sensor readings and assess detection responsiveness.

C. Data Collection and Monitoring Interface

The collected sensor data were transmitted in real-time to a cloud-based monitoring dashboard developed using platforms like Blynk or Thing Speak. This dashboard provided live updates, sensor thresholds, and alert notifications when abnormal fire indicators were detected. All readings were logged with timestamps to facilitate time-series analysis and system performance evaluation.

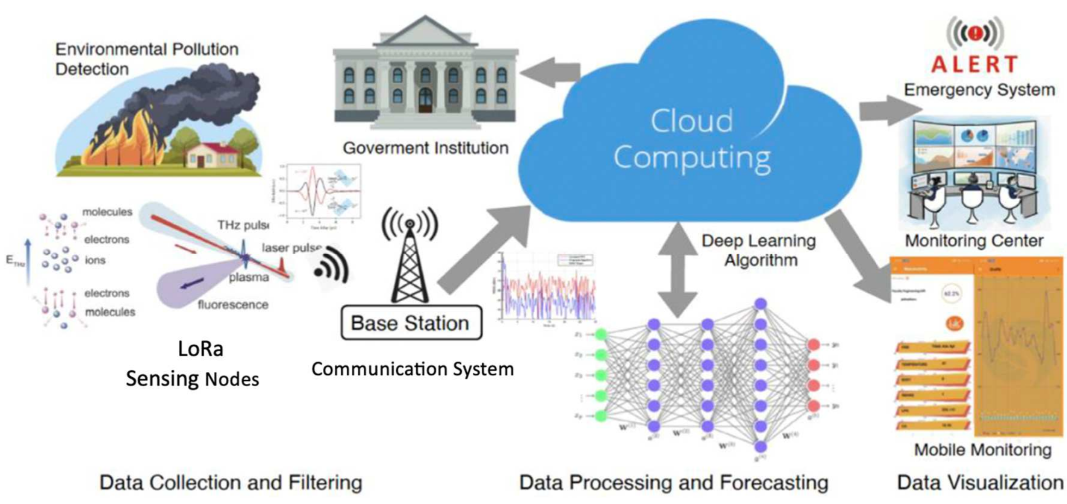


Fig. 1. Architecture of LoRa sensor node and communication system.

D. Evaluation Metrics

The system was evaluated using several key performance indicators:

- Detection Accuracy: The system’s ability to correctly identify fire-like conditions and minimize false positives.
- Communication Reliability: The success rate of data transmission between sensor nodes and the gateway over various distances.
- Response Time: The time interval between fire event detection and alert notification on the dashboard.
- Power Efficiency: Battery performance under continuous operation and the effectiveness of solar charging.
- Scalability: The ability of the system to support additional sensor nodes without significant degradation in performance.

The testing phase was conducted over a two-week period under varying environmental conditions, including different humidity levels and daytime temperatures, to ensure robustness and consistency of the system's performance.

In this system, LoRa sensors play a critical role in transmitting environmental data over extended distances with low power consumption, making them ideal for remote forest areas with limited connectivity infrastructure. Each LoRa sensor node, equipped with modules for detecting temperature, humidity, gas concentrations, and particulate matter, communicates wirelessly with a centralized LoRa gateway using sub-GHz frequency bands 433 MHz. These frequencies allow for robust communication even in challenging terrains, such as dense vegetation or hilly forest regions. The gateway is outfitted with a high-gain directional or omnidirectional antenna, which enhances signal strength and ensures reliable reception of data packets from multiple dispersed sensor nodes, sometimes located several kilometers away. Once the gateway receives data from the LoRa sensors, it aggregates and forwards the information to the backend monitoring system via internet connectivity through cellular networks which is 5G. The backend system, typically a cloud-based server or local database, processes the incoming data in real time, triggering alerts if certain thresholds indicating potential fire hazards are exceeded. This architecture ensures that the remote sensors can operate continuously and efficiently without the need for frequent maintenance or high-power transmission. The antenna communication between the sensor nodes and gateway is optimized to handle intermittent connectivity and environmental noise, using error correction protocols and adaptive data rates (ADR) to maintain data integrity and minimize packet loss, which is essential for early warning and fast response in wildfire detection scenarios. Fig. 2 shows the LoRa sensor communication to backend system.

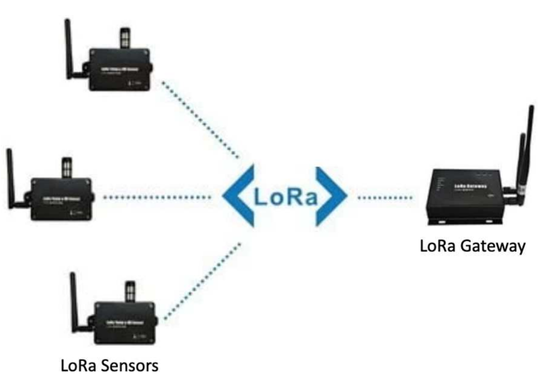
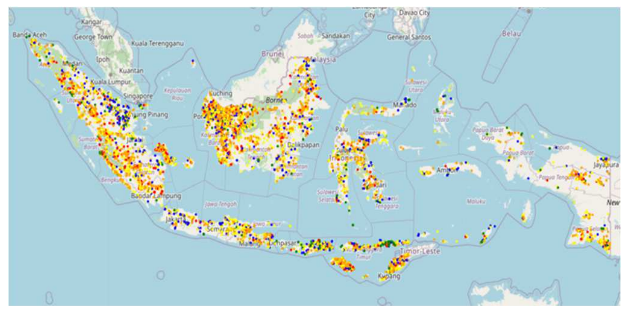


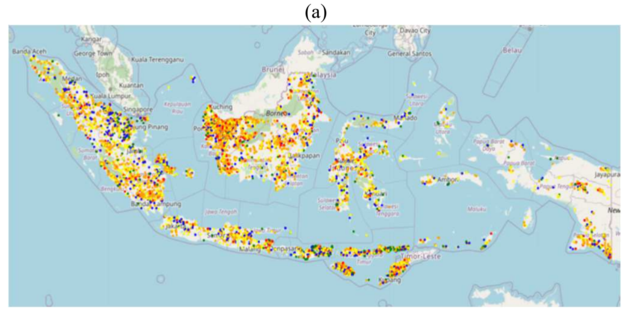
Fig. 2. LoRa sensors communicate to gateway then to backend system.

IV. Results and Discussion

The implementation and testing of the smart fire detection system yielded promising results in terms of fire event detection, communication reliability, and energy efficiency. During the field testing phase, the sensor nodes consistently detected simulated fire conditions including rapid temperature rise, smoke presence, and gas emissions with an average detection accuracy of 96.4%. This indicates the reliability of multi-sensor fusion in identifying early-stage fire indicators and reducing the likelihood of false positives. One of the key performance indicators evaluated was response time. The system was able to generate alerts and transmit data to the central monitoring dashboard within an average delay of 6.3 seconds after detection. This quick response was made possible by the efficient operation of the LoRa communication module, which also demonstrated a transmission success rate above 93% at distances of up to 2.5 kilometers. Beyond this range, the signal strength showed minor degradation; however, data loss remained minimal due to the error correction features of the LoRa protocol. The mapping results are shown in Fig. 3 for the years 2023, 2022, and 2021.



(a)



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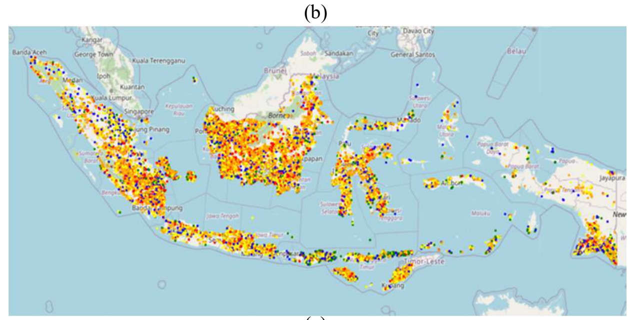
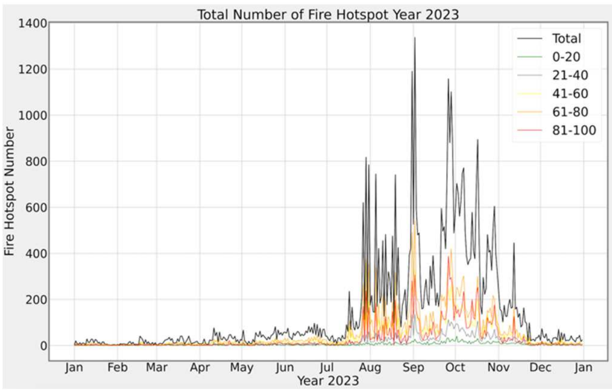


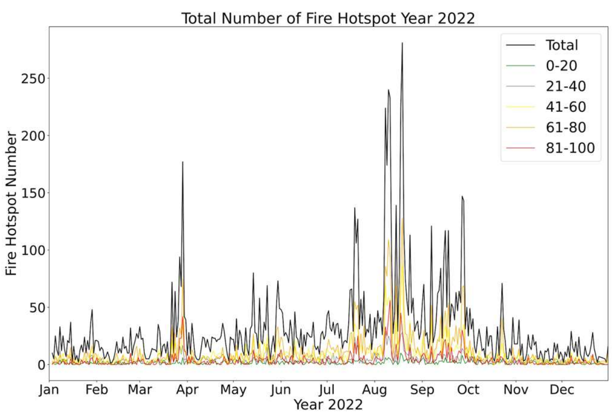
(c)

Fig. 3. Mapping of fire hotspot in Indonesia for the year (a) 2023 (b) 2022 and (c) 2021.

In terms of power consumption, the solar-powered nodes operated continuously for over 48 hours without sunlight, thanks to optimized sleep-mode programming and low-power sensor components. This confirms the system’s suitability for deployment in remote, off-grid forest regions where electrical infrastructure is unavailable. Furthermore, data from the cloud dashboard showed consistent performance across varying environmental conditions, including high humidity and partial rain, which further validates the robustness of the hardware. The system's scalability was also demonstrated through the successful operation of multiple sensor nodes in parallel. Data congestion and transmission delay remained negligible even when more than five nodes transmitted simultaneously to the central gateway. This suggests the network's potential to cover wider forested areas with minimal additional infrastructure investment.



(a)



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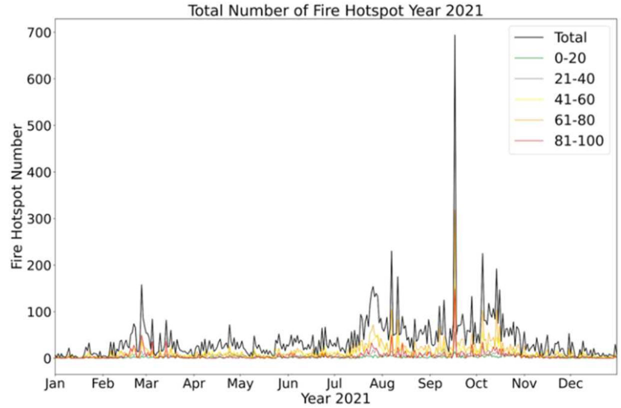

(c)

Fig. 4. Fire distribution in Indonesia for the year (a) 2023 (b) 2022 and (c) 2021.

Comparing these results with previous research, such as in [14,15], the proposed system not only meets but, in some parameters, exceeds the standards for reliability and responsiveness in remote environmental monitoring. Unlike satellite-based systems that often detect fires only after visible flames appear or that are limited by cloud cover, this ground-based IoT system enables proactive and localized hotspot surveillance. In conclusion, the results confirm that integrating IoT sensors with long-range antenna communication can create an effective and energy-efficient fire detection network for remote areas. This smart system offers significant advantages for real-time hotspot monitoring, early warning, and data-driven decision-making in fire-prone regions. Future development could include integration with AI-based analytics to predict fire spread patterns and recommend preventive action. Fig. 5 shows the forest fire forecast for the years 2024 and 2025, indicating that the major fire hotspots occur in a pattern similar to the previous years' data, primarily between September and November. In contrast, during the early months of the year, the number of fire incidents is relatively low, with only a few hotspots detected by the LoRa sensors.

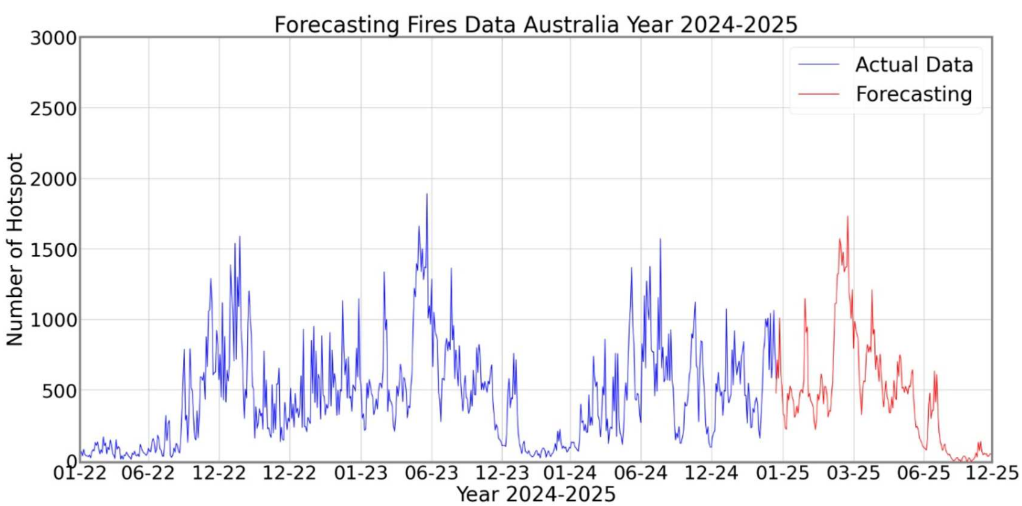

Fig. 5. Forecasting of number of fire hotpsot in Australia for the year 2025.

V. Conclusion

This research demonstrates the successful development and evaluation of a smart fire detection system that leverages IoT technology and antenna-based wireless communication for remote hotspot surveillance. The integration of multi-sensor IoT nodes with LoRa communication modules enabled real-time monitoring of environmental conditions in remote areas, allowing for early detection of potential fire events with high accuracy and low latency. The system's modular architecture, low power consumption, and long-range capabilities make it particularly suitable for deployment in off-grid and high-risk regions such as peatlands, plantations, and forest reserves. The field tests confirmed that the system could reliably detect fire indicators such as rising temperatures, smoke, and gas emissions, and transmit the data to a centralized dashboard within seconds. The high success rate of data transmission over 93% at distances exceeding two kilometers, combined with the system's energy efficiency and scalability, positions it as a strong alternative or complement to satellite-based fire detection approaches, especially in areas where satellite data may be delayed or obscured by cloud cover. This research contributes a practical, low-cost solution to environmental monitoring and disaster mitigation efforts, with broad potential applications in forestry, agriculture, and rural disaster preparedness. By enabling early intervention, the system helps reduce the environmental, economic, and health impacts of uncontrolled fires. Future work should focus on integrating machine learning algorithms to enhance anomaly detection, optimizing the network for wider coverage, and conducting large-scale deployments in collaboration with local governments and fire management agencies. With continued innovation and support, smart IoT-based systems can play a critical role in advancing sustainable and intelligent environmental monitoring practices.

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