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Comparison of Methods for Designing and Deploying an IoT-Based Forest Fire Warning System: A Case Study in An Giang, Vietnam

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Abstract: This paper presents the design and deployment of an IoT-based early warning system for forest fire detection, optimized for remote and infrastructure-scarce environments. The system integrates multiple environmental sensors including air temperature, air humidity, soil moisture, rainfall, wind speed, and wind direction interfaced with ESP32 microcontrollers for local data acquisition. Each sensor node operates autonomously using solar power, enhancing sustainability and long-term field operation. Data is transmitted using LoRaWAN for long-range, low-power communication, with 3G fallback for redundancy in critical zones. A centralized server collects and processes the data in real time, applying a rule-based threshold algorithm combined with temporal trend analysis to detect fire-prone conditions. A web-based dashboard provides monitoring and visualization, while alert notifications are dispatched via SMS and email when risk levels exceed defined thresholds. Field trials conducted in the An Giang region demonstrated reliable communication over distances exceeding 5 km, stable solar-powered operation, and alert latency of under 10 seconds. The results confirm the system's feasibility and effectiveness in providing early warnings for wildfire prevention in rural forest areas.
Keywords: Forest Fire Warning System, Environmental Monitoring, Wireless Sensor Network, Early Warning, Remote Sensing, Wildfire Prevention, Low-Power Communication, Microclimate Sensors

I. INTRODUCTION

Forests are one of the most valuable natural resources of any nation, and in Vietnam, they are given top priority in conservation and protection efforts. However, each year, the country faces several wildfire incidents of varying magnitudes, largely due to prolonged dry weather and climate changes. The monitoring and collection of environmental data in forest areas to enhance forest fire risk warning systems is of utmost importance to prevent catastrophic outcomes [1].

To assess the risk and likelihood of forest fires accurately, it is essential to gather precise weather data in the forest, including parameters such as temperature, humidity, rainfall, and wind conditions. However, traditional methods of collecting such data often involve significant time and labor, and the collected data may not be updated regularly enough to provide timely and accurate warnings. Consequently, the development and implementation of an IoT-based forest fire warning system are crucial for automating data collection, ensuring its accuracy, and providing timely alerts. The system proposed in this study is designed to address these challenges by utilizing advanced technologies to automatically monitor and collect weather data in real-time. By implementing an IoT network, we aim to provide continuous environmental monitoring and facilitate accurate fire risk analysis, which is essential for proactive forest fire management. Given the unique conditions of forest environments, we explored various solutions to ensure the system's effectiveness and reliability in the field. After several iterations involving changes in sensor equipment and data collection models, due to factors such as frequent rainfall, power supply issues, and network connectivity, we have proposed a final system model that has been successfully deployed and tested at the An Giang Forest Protection Department. Two system models were considered: (1) an IoT-based wireless network using LoRa (Long Range) technology combined with internet connectivity and power supplied from the grid; and (2) a model using mobile network technologies (GPRS/3G/4G) along with solar power. After practical experimentation in the forest, we found that the mobile network and solar power model better suited the local infrastructure and environment. Data from the system is monitored and managed through a web-based platform hosted on a central server, providing real-time access for stakeholders. This allows forest managers and local authorities to track environmental conditions and fire risk levels continuously, with fire risk alerts being displayed on the website. This approach empowers both the public and forest management personnel to take prompt actions in case of potential fire hazards, contributing to timely prevention and mitigation of forest fires.

II. RELATIVE WORKS

The application of IoT technology in forest fire detection systems has gained significant attention in recent years. These systems leverage wireless sensor networks (WSNs) and other related technologies to monitor environmental conditions in forests and predict the likelihood of fire outbreaks, helping mitigate the damage caused by wildfires. Several key studies in this area have contributed to the development of such systems.

Zong et al. explored the impacts of climate change on wildfire risk in Central Asia. Their research demonstrated that rising temperatures and decreasing humidity were significant factors in increasing the frequency and severity of wildfires. By using climate data-based prediction models, fire detection systems can significantly improve early fire risk detection, making them a valuable tool in the prevention and management of forest fires [1].

Sáez et al. introduced an IoT-based sensor system for monitoring forest environments and detecting wildfire risks. The system utilizes sensors to measure temperature, humidity, and rainfall, combined with machine learning algorithms that analyze the data to predict fire outbreaks. The system has been successfully tested in forest areas across Spain, showing the practical application of IoT for wildfire prevention [2].

Ghosh et al. proposed a wireless sensor network (WSN) for monitoring environmental factors in forests and detecting fire risks. The network includes devices to measure temperature, humidity, and wind speed, providing real-time data for monitoring. This approach was successfully implemented in conservation areas in India, demonstrating the effectiveness of WSNs in wildfire detection and management [3].

Carvalho et al. focused on the development of fire risk prediction models that utilize environmental and climatic data. These models combine factors such as temperature, air humidity, and rainfall to forecast the likelihood of fire outbreaks. Their research suggests that machine learning models based on climate data can significantly improve the accuracy and reliability of fire prediction systems, further enhancing the capabilities of IoT-based fire detection systems [4].

In remote forest areas, a critical challenge is providing reliable and sustainable power sources for IoT-based sensor systems. Rani et al. addressed this issue by developing a solar-powered system to supply energy to forest monitoring sensors. Tested in remote locations in India, this system demonstrated stable operation in harsh environments and helped reduce operational costs, making it an ideal solution for forest areas with limited infrastructure [5].

Firoz et al. discussed the challenges involved in deploying forest fire detection systems, including network connectivity, energy supply, and sensor data accuracy. They proposed solutions such as using LoRaWAN for long-range communication and solar power to provide sustainable energy for sensor stations. These innovations help overcome the limitations of traditional fire detection systems, making them more feasible for widespread implementation [6].

These studies underscore the importance of integrating IoT technology, wireless sensor networks, and climate prediction models to create more efficient forest fire detection systems. The research emphasizes that IoT-based systems, with real-time data collection and analysis, can play a crucial role in early fire detection, particularly in remote or underserved areas.

III.METHODOLOGY

The methodology for the development and implementation of the forest fire monitoring system is divided into two main approaches based on the communication technologies used for data transmission: the 3G mobile network and the LoRa wireless network. Each method was selected to address specific environmental conditions and infrastructure capabilities, ensuring flexibility in deployment and effectiveness in different locations.

In the first approach, the system utilizes the 3G mobile network (GPRS/3G) for transmitting collected data to a central server. This method is suitable for areas with reliable cellular network coverage, as it allows for real-time data transmission over the internet. The system consists of several components that work together to monitor environmental parameters, including air temperature, humidity, wind speed, and soil moisture. The data is sent via a SIM800A module, which establishes the connection to the mobile network, enabling the transmission of the sensor data to the server.

The second approach incorporates LoRa (Long Range) technology, which is designed for low-power, long-range data transmission. LoRa is particularly advantageous for remote or off-grid areas where cellular coverage may be unreliable or unavailable. In this approach, the environmental data is transmitted over long distances using LoRa wireless communication. The system includes the same set of environmental sensors, such as temperature, humidity, and wind sensors, but the data is sent to a LoRa gateway, which then relays it to the central server via the internet.

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Both methods were designed with energy efficiency in mind, using solar panels and batteries to power the systems. Solar energy ensures that the systems remain operational in locations where access to electricity is limited or unstable. While the 3G-based system is more suited to areas with established mobile networks, the LoRa-based system provides a reliable alternative for remote regions, offering better energy efficiency and longer transmission ranges.

In conclusion, the choice of technology depends on the specific conditions of the deployment area. The 3G-based system provides faster and more frequent data transmission, making it suitable for regions with stable cellular coverage. On the other hand, the LoRa-based system offers a more suitable solution for remote areas with limited network infrastructure, providing long-range, low-power communication for continuous monitoring of forest fire risks.

A. Real-Time Data Transmission via 3G Mobile Network for Forest Fire Monitoring

The proposed method for forest fire detection utilizes a 3G-based communication system to collect and transmit environmental data to a central server (Figure 1). This method ensures reliable data transmission over long distances, particularly in remote forest areas where other communication infrastructure may be unavailable. The system uses the SIM800A module, which connects to the mobile network and facilitates the transmission of sensor data. This approach is suitable for areas with mobile network coverage and provides real-time data updates for monitoring and analysis.

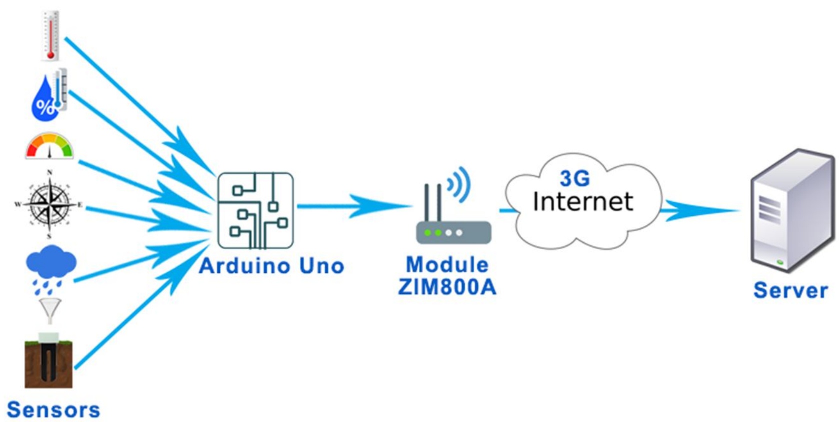

Figure 1: Data Collection System Model Using 3G Network

The core of the system is an Arduino Uno R3 microcontroller, which is responsible for collecting data from various sensors. These sensors include a wind speed and direction sensor, a temperature and humidity sensor (DHT22), a soil temperature and humidity sensor (SHT10), and a rainfall sensor. The Arduino processes the data from these sensors and sends it to the server via the 3G network. The system also uses a solar panel to provide energy for continuous operation in remote locations where access to the power grid is limited (Figure 2).

A key feature of the system is its low power consumption. The microcontroller and sensors are powered by a 12V battery, which is charged by the solar panel. A solar charge controller manages the charging process and protects the battery from overcharging or deep discharge. This setup ensures that the system operates continuously, even during cloudy or rainy periods, providing reliable data collection for fire risk assessment.

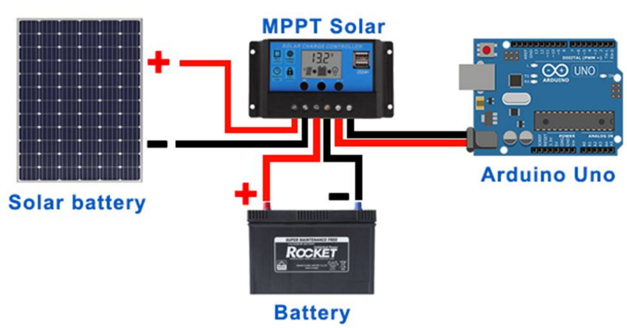

Figure 2: Model Utilizing Solar Power Supply

The data collected by the sensors includes air temperature, air humidity, soil temperature, soil moisture, wind speed, wind direction, and rainfall. The air temperature, air humidity, and rainfall data are the primary inputs used to calculate the meteorological fire index (P), which is essential for assessing the risk of forest fires. This index is calculated using the formula:

$$P_i = K * \sum_{i=1}^{n} T_{i13} \times D_{i13} \quad (1)$$

- P_i is the meteorological index on day i, used to evaluate the fire danger level.
- K is a coefficient with a value of 1 when the rainfall on day i is less than 5 mm, and 0 when the rainfall is equal to or greater than 5 mm.
- T_{i13} is the maximum air temperature recorded at 13:00 on day i.
- D_{i13} is the vapor pressure deficit (difference between saturated and actual humidity) at 13:00 on day i.
- n is the number of consecutive days without rainfall or with rainfall less than 5 mm, counted from the last day that recorded a rainfall of 5 mm or more.

The fire risk level for each day is assessed based on the value of the meteorological fire index P, and the warning level is determined using a predefined scale that categorizes the risk of fire into five levels, from low to extremely dangerous.

This method provides an effective and reliable solution for remote forest fire monitoring, with the ability to transmit real-time data and issue fire risk warnings to authorities, enabling timely preventive actions. The risk of forest fire for a given day is determined based on the fire weather index, with the fire danger level being assessed according to the classification provided in the regulations set forth by the Ministry of Agriculture and Rural Development of Vietnam (Decision No. 2059 NN/KHCN/QĐ, 1997) show in Table I.

TABLE I: FOREST FIRE WARNING LEVEL CLASSIFICATION TABLE BASED ON METEOROLOGICAL INDEX P

Fire Danger Level	P Index Range	Characteristics of Fire Risk
I	<5000	Low: Low risk of fire
II	5001-10,000	Moderate: Possibility of fire
III	10,001-15,000	High: Likely to catch fire
IV	15,001-20,000	Very High: High risk of fire
V	>20,000	Extreme: Rapidly spreading fire

B. Long-Range Data Communication for Forest Fire Detection using LoRa Technology

To enhance the effectiveness of the fire warning system in remote areas, we initially explored the use of both mobile network-based and LoRaWAN-based solutions for data transmission. The combination of sensor networks and long-range communication technologies plays a pivotal role in monitoring environmental factors that contribute to fire risks. After careful consideration of the local conditions and available infrastructure, we developed two distinct approaches to address the challenges of remote data collection and transmission.

The first approach employs a 3G mobile network, utilizing the GPRS/3G communication module to transmit sensor data to a remote server for analysis and monitoring. This solution offers the advantage of utilizing existing mobile network infrastructure, ensuring reliable data transmission over long distances. It allows for continuous data flow from the sensors to the central system, even in areas with limited access to other communication options.

The second approach involves the use of LoRaWAN (Long Range Radio Wide Area Network), a low-power, wide-area network technology that is highly effective in environments where connectivity via mobile networks is limited or unavailable (Figure 3). LoRaWAN allows for the transmission of data over several kilometers, making it ideal for monitoring large forested areas. By leveraging LoRa technology, which operates at the physical layer of the LoRaWAN protocol, this model connects nodes (sensors) to gateways that relay the data to the central server. This method reduces dependency on conventional network infrastructure while ensuring efficient, long-range communication in remote areas.

Both approaches were designed to meet the unique demands of our fire detection system, balancing the need for reliability, low power consumption, and long-range communication. By evaluating the feasibility of each method based on the region's specific needs and constraints, we can determine the most suitable solution for continuous, real-time environmental monitoring.

The system is designed to monitor key environmental parameters that can indicate the risk of forest fires, such as temperature, humidity, wind speed, and rainfall. These data points are crucial for predicting fire risks, and the system utilizes a combination of sensors and communication technologies to gather and transmit data effectively. The system architecture consists of several components, each playing a vital role in ensuring efficient data collection, transmission, and processing.

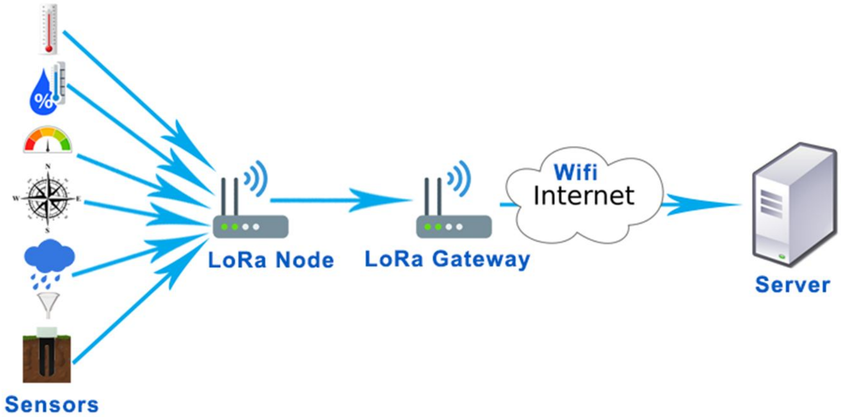

Figure 3: System Model Using LoRaWAN Network

1) System Components

The system consists of several key components, each designed to play a specific role in monitoring and transmitting environmental data for fire risk prediction. The primary components include the sensors, nodes, LoRa modules, gateway, network server, and application server.

- Sensors are responsible for measuring various environmental parameters, including temperature, humidity, wind speed, direction, and rainfall, all of which are essential for assessing the fire risk level.
- Nodes are devices that collect data from the sensors and prepare it for transmission. Each node aggregates data from multiple sensors, encodes it into a data packet, and sends it to the gateway using a wireless communication protocol.
- LoRa Modules are integrated into the nodes, enabling long-range communication over low-power radio frequencies. These modules ensure that data can be transmitted over several kilometers, which is crucial for remote forest areas.
- Gateways serve as intermediaries that receive data from the nodes and forward it to the network server. They act as a bridge between the low-power sensor nodes and the high-performance server infrastructure.
- Network Servers manage and process the data coming from multiple gateways, ensuring proper routing and handling of data before it is sent to the application server.
- Application Servers store and process the incoming data, providing a user interface for monitoring the fire risk levels in real-time. The data is visualized through a web application or mobile app, enabling easy access and decision-making for forest management personnel.

Together, these components form a comprehensive system that efficiently collects, transmits, and processes environmental data, providing timely fire risk alerts and insights for forest management.

2) LoRaWAN Architecture

LoRaWAN is a low-power, wide-area network protocol designed to facilitate long-range communication in remote and rural areas. It is especially useful for environments like forests, where traditional communication infrastructure may be lacking. The LoRaWAN architecture is composed of several key components.

- End Nodes: These are devices (such as the sensor nodes in our system) that collect and transmit data. End nodes are equipped with LoRa radios that allow them to communicate with gateways over long distances.
- Gateways: Gateways are responsible for bridging communication between end nodes and the network server. They receive LoRa signals from nodes and send them to the network server via standard IP-based protocols (e.g., Ethernet, Wi-Fi, or cellular). A single gateway can cover a large area and handle communication with multiple nodes.
- Network Server: This server manages the communication between nodes and gateways. It ensures that data packets are correctly processed, handled, and forwarded to the application server. The network server also manages the network's overall security, including encryption and data integrity.
- Application Server: This server processes the data from the network server and presents it to users in an accessible format. It handles tasks such as displaying environmental data, generating fire risk alerts, and providing actionable insights.

3) LoRaWAN Communication Flow

The LoRaWAN communication flow in the fire warning system is designed to ensure reliable, low-power, long-range transmission of environmental data from sensor nodes to a central monitoring platform. The flow begins at the sensor node, where data such as air temperature, humidity, wind speed, and rainfall are collected at fixed intervals (e.g., every 5–7 minutes). This data is then encoded—typically in a lightweight format like JSON—for efficient transmission.

Once encoded, the data packet is sent via a LoRa module (e.g., SX1278) from the sensor node to the LoRa gateway. The gateway is responsible for receiving data from multiple nodes and forwarding it to the network server over a Wi-Fi or Ethernet connection. Due to the long-range capabilities of LoRa, the system can operate effectively in remote forest locations where cellular or wired networks are not available.

The LoRaWAN protocol ensures that data collisions are minimized and packets are securely transmitted, even when multiple nodes are active simultaneously. The gateway listens for incoming messages from all nearby nodes and can handle overlapping transmissions using spreading factor diversity, which allows the network to scale efficiently.

At the gateway, the incoming data is processed by an ESP8266 microcontroller, which decodes the message and checks for internet connectivity. If a valid Wi-Fi connection is established, the data is uploaded to a central server for further analysis. On the server side, the data is stored in a database and visualized through a web interface, where users can monitor live environmental conditions and fire risk levels.

- A simplified algorithm governing the communication flow operates as follows:
- Initialize sensor interfaces and begin data collection loop.
- Read sensor values and package the data into a structured JSON format.
- Transmit the JSON payload from the node via LoRa to the gateway.
- The gateway receives the payload, decodes it, and converts it to a server-compatible format.
- Establish a Wi-Fi connection and upload the data to the central server.
- Display the data in real-time on the web dashboard, and calculate fire risk based on predefined meteorological formulas.

This efficient communication model enables continuous, real-time environmental monitoring in remote areas while minimizing power consumption—making it ideal for forest fire warning systems where power and connectivity are limited.

C. Benefits of Using LoRaWAN

LoRaWAN offers several advantages that make it ideal for forest fire monitoring systems:

- Long Range: LoRaWAN supports long-range communication, enabling the system to cover large forest areas without the need for multiple repeaters or infrastructure.
- Low Power Consumption: LoRaWAN's low power requirements ensure that the system can operate for extended periods without needing frequent battery replacements.
- Scalability: The LoRaWAN network is highly scalable, meaning additional nodes can be easily added to expand monitoring coverage as needed.
- Cost-Effectiveness: LoRaWAN reduces reliance on expensive mobile networks or other communication infrastructure, making it an affordable solution for remote areas.

This architecture is perfectly suited for forest fire monitoring in remote locations, where traditional communication infrastructure may not be available. By utilizing LoRaWAN, the system ensures reliable data transmission over long distances while maintaining low energy consumption and cost efficiency.

D. The Proposed LoRaWAN-based forest fire warning system

The proposed LoRaWAN-based forest fire warning system is engineered to deliver a reliable, energy-efficient, and long-range communication infrastructure tailored for deployment in remote and forested regions of An Giang province, Vietnam. By leveraging the low-power characteristics of LoRa technology and integrating renewable energy sources, the system is well-suited for areas with limited or no access to conventional power grids. It operates autonomously 24/7 using solar energy, thus ensuring uninterrupted functionality even during extended periods of power outages or in isolated locations far from urban infrastructure.

The system is structured around a four-layer architecture comprising the Sensor Nodes, LoRa Gateway, Network Server, and Application Layer. Each layer plays a critical role in the acquisition, transmission, processing, and visualization of environmental data to support forest fire risk assessment.

At the Sensor Node level, each device acts as a localized data acquisition station and wireless transmitter. The core component of the node is an Arduino Uno R3 microcontroller, which is programmed to read environmental data from various sensors at fixed intervals, typically every five minutes. These sensors include the DHT22 for measuring air temperature and humidity, the SHT10 for soil temperature and moisture, a wind speed and direction sensor, and a tipping bucket rain gauge for rainfall data collection. The collected data is then encoded into JSON format and transmitted using the SX1278 LoRa module operating at 433 MHz. This module supports a default data rate of 2.4 Kbps (adjustable between 0.3 and 19.2 Kbps) and a transmission range of up to 3 km in open conditions. The entire node is powered by an off-grid solar energy setup that includes an 80W solar panel, a solar charge controller, and a 12V–40Ah lead-acid battery, enabling sustainable operation throughout the year.

The environmental data collected from these nodes is used to compute the P-index, a meteorological index that quantifies forest fire risk. This index incorporates key variables such as maximum air temperature at 13:00, the vapor pressure deficit (reflecting atmospheric dryness), and the rainfall conditions in previous days. The P-index value increases with higher temperatures and lower humidity, effectively indicating drier and more flammable forest conditions. Based on the computed value, fire risk is categorized into five danger levels: Level I (Low), Level II (Moderate), Level III (High), Level IV (Very High), and Level V (Extreme). This classification provides an evidence-based foundation for forest rangers and disaster management teams to initiate timely preventive actions or emergency responses.

The LoRa Gateway acts as a bridge between the sensor network and the internet. It is equipped with an additional SX1278 module to receive data packets transmitted from the sensor nodes. An ESP8266 microcontroller decodes the packets and prepares them for onward transmission via Wi-Fi. The ESP8266 also runs a web-based configuration interface that allows field technicians to set up Wi-Fi credentials directly on-site. This is done through a captive portal with a login interface to ensure secure access and avoid unauthorized configuration changes.

Data received at the gateway is relayed to a centralized cloud server via HTTP or HTTPS, using standard RESTful APIs. The server infrastructure includes a MySQL database where the data is stored for further analysis. Upon receiving new data, the server processes the information to recalculate the daily P-index and assess the corresponding fire risk level. Results are then visualized on a web-based dashboard, which presents real-time sensor readings (e.g., temperature, humidity, wind speed, rainfall) and trend charts. The dashboard supports data download for archival purposes and historical analysis, making it a powerful tool for decision-makers and researchers monitoring fire hazards over time.

The data communication flow and algorithm within the system follow a structured sequence to ensure data reliability and timely delivery. The Arduino microcontroller initiates the cycle by collecting data every 5–7 minutes from all connected sensors. The data is then encoded into a JSON-formatted string and sent wirelessly to the gateway via LoRa transmission. Upon reception, the gateway validates and decodes the packet, checks for integrity, and uses the ESP8266 module to upload the data to the cloud server using a POST request. The server processes this data to calculate the P-index, compares the result to predefined thresholds, and assigns a fire danger level. The outcome is made immediately accessible through the online dashboard, allowing forestry officials to monitor conditions and respond proactively. This comprehensive and self-sustaining IoT-based solution provides an effective means of monitoring environmental conditions for early fire warning, and its implementation in An Giang province demonstrates its potential for broader adoption in similar rural or mountainous regions. The image below (Figure 4) illustrates the deployment of the IoT-based forest fire warning system in An Giang, Vietnam. It highlights the integration of sensor nodes, the LoRaWAN communication network, and the central server, which are all connected to a solar-powered system to ensure continuous operation in remote areas. This setup is designed to monitor environmental parameters in real-time and transmit the data for processing and visualization through a web-based interface, providing early warning alerts for forest fire risks.

Figure 4: Deployment of the IoT-Based Forest Fire Warning System in An Giang, Vietnam

IV. EXPERIMENTAL RESULTS

After two years of field testing and system evaluations, both LoRaWAN and 3G-based models have demonstrated the feasibility of deploying IoT for forest fire early warning. However, the LoRaWAN model, while cost-effective, faced limitations due to unreliable power supply and local internet infrastructure. In contrast, the 3G-based model proved more suitable for the actual conditions in An Giang province, especially when integrated with an optimized solar energy system to ensure continuous operation.

All collected data was transmitted to a centralized web server powered by a MySQL database. Environmental parameters such as air temperature, humidity, soil moisture, dew point, wind speed and direction, and rainfall were logged at 5–7-minute intervals. The fire risk index (P value) was automatically calculated based on the daily maximum temperature at 13:00, with a scheduled server-side script triggered every midnight. This computation determined the fire risk level (from I to V) according to Vietnamese forestry standards. Results were displayed on a live monitoring website, allowing users to track real-time status from anywhere with internet access.

The comparative analysis between the 3G-based and LoRaWAN-based models is shown in Table II.

TABLE II: COMPARISON BETWEEN 3G NETWORK MODEL AND LORAWAN NETWORK MODEL

Criteria	3G Network Model	LoRaWAN Network Model
Cost	High operational cost	Low deployment and operational cost
Energy Consumption	High energy consumption	Low energy consumption
External Impacts	Prolonged rainy days lead to solar power shortages	Power outages disrupt Wi-Fi and Gateway operation
Device Reliability	SIM800A module often fails to connect to 3G	LoRa transceivers are susceptible to signal interference
Operational Time	Operates continuously 24/7	Operates continuously 24/7

The IoT data collected during the critical monitoring period (12:30–13:30 daily) includes the fire index values and corresponding warning levels, as summarized in Table III.

TABLE IIII: SAMPLE DATA COLLECTED AND DAILY WARNING

Date	Air Temp (°C)	Air Humidity (%)	Soil Moisture (%)	Dew Point (°C)	Wind Speed (Level)	Wind Direction	Rainfall (mm)	Pi Index	Danger Level
19/12/24	35.50	52.81	75.17	21.82	8	North	0.00	5520.98	2
18/12/24	39.00	48.12	75.00	23.72	8	North	0.00	5035.34	2
17/12/24	36.70	57.27	75.80	22.45	5	Northwest	0.00	4572.49	1

V. CONCLUSIONS

This study proposed and experimentally deployed two IoT-based solutions for forest fire early warning in Tinh Bien district, An Giang province: one using LoRaWAN technology and another using 3G-based communication. Both systems operated reliably and delivered real-time data and fire risk estimates. However, the 3G-based model proved more appropriate given the current local infrastructure, particularly in terms of internet access and electricity availability. The system performed autonomous data acquisition every 5–7 minutes, continuously throughout the day, providing accurate daily calculations of the fire index (P value). Data was uploaded to a cloud-based web dashboard, enabling forest rangers and management agencies to monitor risk levels conveniently, anytime and anywhere.

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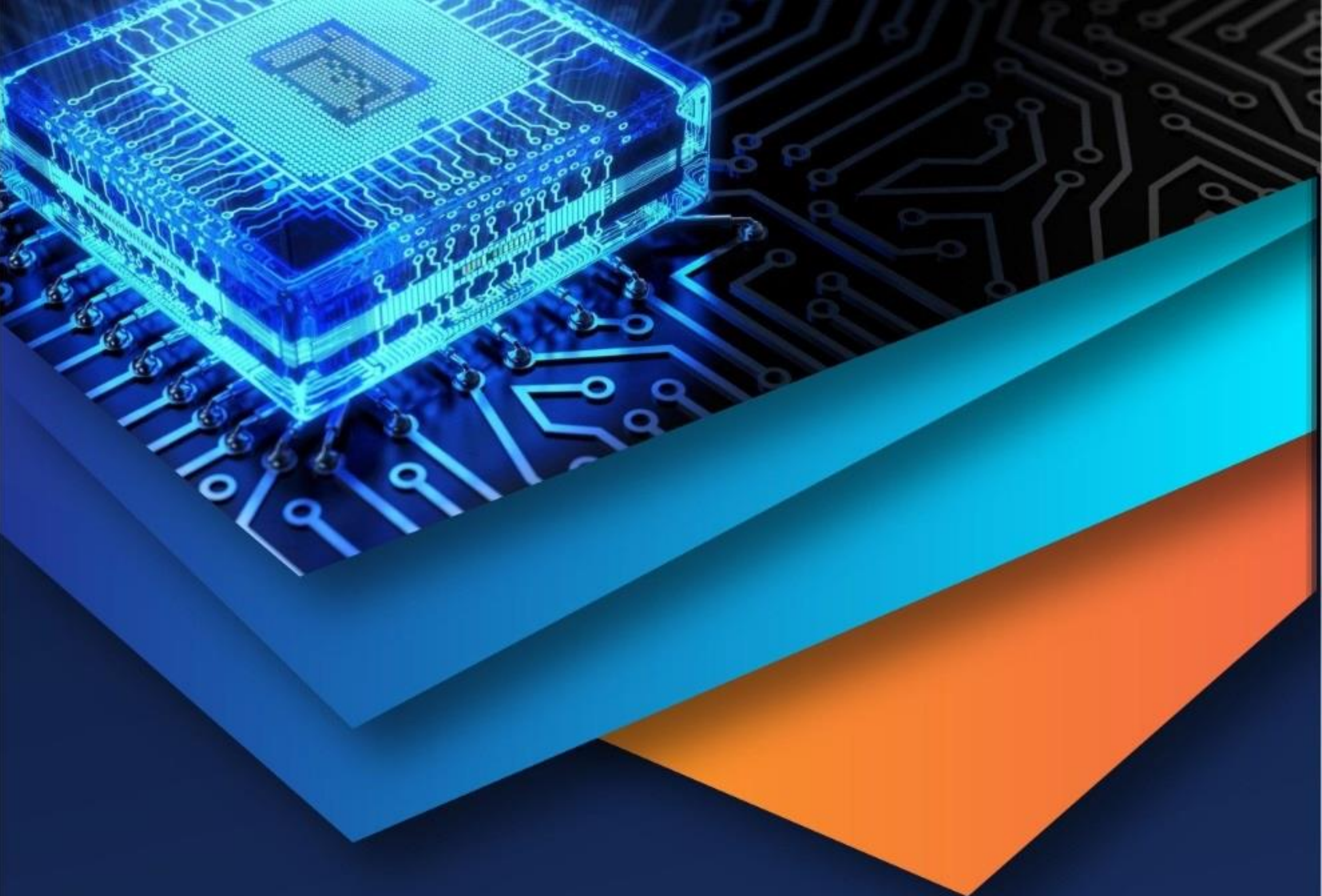

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