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A Lora-Based Geofencing System For Real-Time Elephant Movement Monitoring And Early Warning

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ABSTRACT

This research aims to develop a LoRa-based geofencing system for real-time elephant movement monitoring and early warning. The system implements a radius-based geofencing method, where a circular virtual boundary is defined using a center coordinate and a predefined radius. The distance between the elephant's GPS position and the geofence center is calculated to determine whether the elephant is inside or outside the designated safe zone. The system transmits sensor and location data from the LoRa gateway to the server using the MQTT protocol and displays information in real time through a web-based dashboard. This architecture supports remote monitoring with low latency and wide communication coverage. Experimental results show that the average data transmission time from the gateway to the server via MQTT is 1.44 ms, while the average notification delivery time to users is 0.89 seconds. The system maintains stable communication up to a distance of 1 km with an RSSI value of −105 dB. Furthermore, the developed dashboard was successfully deployed online, enabling real-time monitoring of sensor data, geofence status, and device conditions through an interactive interface. These results indicate that the proposed LoRa-based geofencing system provides efficient communication performance, low latency, and reliable early warning capability, making it suitable for remote wildlife monitoring and other IoT-based applications.

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1. INTRODUCTION

Monitoring elephant movement is a fundamental component of wildlife conservation and human–wildlife conflict mitigation strategies. Elephants are wide-ranging species [1], [2] that are highly vulnerable to poaching, habitat degradation [3], and the increasing frequency of human–elephant conflict (HEC) [4], [5]. In many tropical forest regions, habitat fragmentation and land-use conversion have significantly reduced available natural corridors, forcing elephants to move closer to agricultural land and human settlements. This spatial overlap has intensified conflict incidents, resulting in economic losses, infrastructure damage, and safety risks for both local communities and elephant populations. Consequently, the development of an effective, real-time, and reliable monitoring system has become increasingly critical to support conservation management and early mitigation efforts.

Conventional elephant tracking systems relying on GPS and radio communication present several practical limitations, particularly in remote forest environments. Restricted signal coverage, high energy consumption, and elevated operational costs limit their scalability for large conservation areas [6]. In addition, limited battery endurance frequently leads to discontinuous tracking data, potentially reducing the responsiveness of conservation interventions. Previous elephant detection systems employing Passive Infrared (PIR) sensors combined with GSM communication [7], [8] demonstrate basic detection capability; however, their performance is often constrained by sensing reliability and unstable data transmission. GSM networks are highly dependent on cellular infrastructure and terrain conditions, which are typically unfavorable in dense forest habitats where signal availability is inconsistent.

LoRa (Long Range) communication technology has emerged as a promising alternative due to its long transmission range and ultra-low power consumption characteristics. This technology enables efficient delivery of elephant location data over wide areas, even in regions with limited or no cellular connectivity [9]. The integration of LoRa with GPS modules enhances location tracking capability while maintaining lower operational costs compared to conventional radio or GSM-based systems [10]. Nevertheless, studies have reported performance degradation when LoRa devices are deployed in dense tropical rainforest environments, where vegetation density and environmental factors affect signal propagation quality and hardware durability.

In forest environments, radio signal propagation becomes considerably more complex due to vegetation density, tree trunks, humidity, and irregular terrain profiles. [ADDED] Signal attenuation caused by foliage absorption, multipath fading, shadowing effects, and non-line-of-sight (NLOS) propagation can significantly reduce the effective link budget. Path loss characteristics in tropical forests are typically higher than those observed in open rural areas, thereby influencing communication range, packet delivery ratio, and latency. As a result, transmission reliability depends not only on distance but also on parameter configuration and environmental conditions. A thorough understanding of attenuation behavior in forested environments is therefore essential to ensure dependable LoRa-based wildlife monitoring systems. [END-ADDED]

LoRa technology has also been implemented in wildlife and livestock monitoring applications with encouraging outcomes. For example, prior research developed an elephant activity monitoring system using LoRa and gyroscope sensors to collect real-time movement and posture data. The system visualized geographic coordinates on digital maps alongside activity indicators such as standing or lying positions, supporting behavioral analysis in natural habitats. However, this work primarily emphasized activity monitoring and did not incorporate a geofencing mechanism to provide early warnings for potential human–elephant conflicts [11].

Similarly, LoRa-based Internet of Things (IoT) systems have been applied to livestock monitoring within predefined virtual boundaries (geofencing). These systems generate alerts when animals move beyond designated areas, demonstrating the feasibility of virtual fencing concepts [12]. Although effective in controlled livestock environments, deploying such mechanisms in large-scale forest ecosystems introduces additional challenges, including broader coverage requirements, environmental attenuation, and device durability under harsh outdoor conditions.

The geofence concept, defined as a virtual boundary established using geographic coordinates, represents a critical feature for proactive elephant movement management. Through radius-based geofencing and distance calculation algorithms, the system can automatically detect boundary crossings and trigger real-time warning notifications. However, practical implementation of geofencing often reveals discrepancies between the predefined virtual boundary and the actual spatial behavior recorded by positioning systems. Positioning inaccuracies, signal instability, and environmental obstructions may cause spatial spillover beyond designated boundaries. In positioning-based systems, such inaccuracies can generate false positives (detections outside the intended boundary) or false negatives (failures to detect entities within the boundary). Therefore, defining appropriate geofence parameters, minimizing false alarms, and ensuring low-latency alert transmission remain significant technical challenges, particularly in expansive and densely vegetated conservation areas.

Other approaches have utilized image-based detection techniques to identify elephant presence. While effective in certain scenarios, these methods require substantial computational resources and higher power consumption, limiting their suitability for distributed, large-scale deployment in resource-constrained forest environments [10]. In addition, artificial intelligence and machine learning methods have been employed to analyze movement data collected from LoRa and GPS sensors to predict routes and identify potential threats [13][14]. Despite their analytical advantages, these approaches remain highly dependent on stable network connectivity for continuous data transmission to centralized servers, which is often difficult to maintain in remote conservation regions [15][16].

Despite the rapid development of LoRa-based wildlife monitoring and geofencing applications, an integrated framework that simultaneously addresses long-range low-power communication reliability in forest environments and accurate geofence-based early warning for human–elephant conflict mitigation remains limited. Existing studies tend to focus either on movement tracking, activity classification, or communication performance, without thoroughly examining the interaction between environmental attenuation, positioning uncertainty, and real-time boundary detection reliability in large-scale conservation areas. Furthermore, challenges related to link stability, false geofence triggering, and latency-sensitive alert delivery in dense tropical forests have not been comprehensively investigated within a unified system architecture.

Therefore, this study aims to design and evaluate a LoRa- and geofence-based elephant monitoring system that emphasizes communication reliability under forest propagation conditions while ensuring accurate and low-latency early warning performance. By integrating communication parameter considerations with boundary detection mechanisms, this research seeks to contribute a more practical and field-adapted approach to mitigating human–elephant conflict in remote conservation landscapes.

2. METHOD

2.1. System Design

The system design involves a comprehensive architectural approach covering all major functional components. Figure 1 illustrates the overall block diagram of the proposed elephant monitoring system, describing the interaction between the tracking device, communication infrastructure, central server, and user interface.

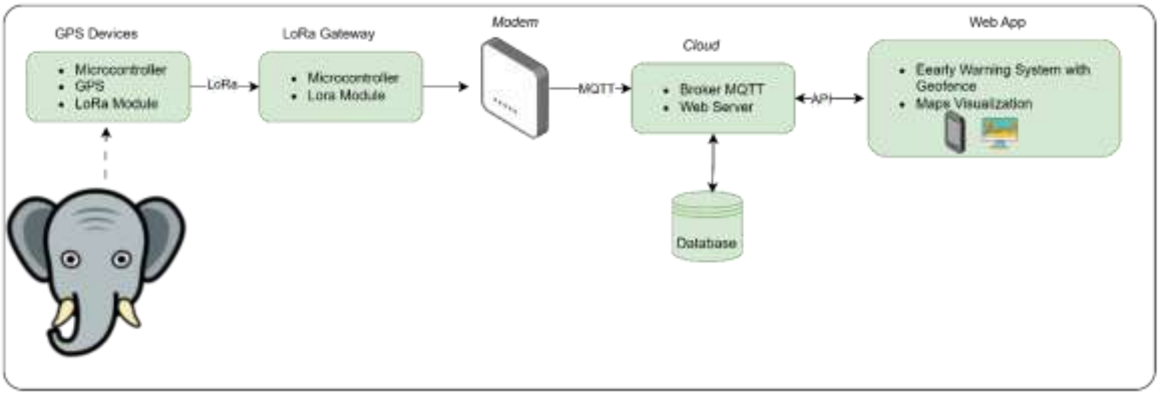

Figure 1. Block Diagram of the Elephant Monitoring System

The elephant monitoring system designed in this study consists of four main components: the GPS tracking device, the LoRa gateway, the central server, and the user interface, all of which are interconnected to form an integrated monitoring system.

The first component is the GPS tracking device, which comprises a microcontroller, a GPS module, and a LoRa module. The microcontroller functions as the primary controller responsible for acquiring coordinate data from the GPS module. The positional data are then transmitted periodically to the gateway via the LoRa module. LoRa is selected due to its long communication range and low power consumption, making it well-suited for monitoring applications in extensive areas such as elephant habitats.

The second component is the LoRa gateway, which also consists of a microcontroller and a LoRa module. The gateway serves as the receiver of data transmitted from the GPS tracking device. Once the data are received, the gateway microcontroller forwards them to the central server via an internet connection. Internet access is provided through a modem device with network connectivity. The data transmission from the gateway to the server utilizes the MQTT (Message Queuing Telemetry Transport) protocol. This protocol is selected due to its lightweight architecture and efficiency in handling periodic data communication within IoT systems.

Subsequently, the data transmitted by the gateway are received by the cloud-based central server. On the server side, an MQTT broker is deployed to manage data reception and distribution from the gateway to other system components, such as the web server and the database. The web server provides an Application Programming Interface (API) that enables data storage in the database for further processing and visualization. The central server acts as the core component responsible for centrally managing all location and movement status data of the monitored elephants.

The final component is the user interface, which is implemented as either a mobile application or a web-based application. This interface functions to visually present monitoring results and generate early warning notifications. Through the web server, users can access real-time elephant position data displayed on digital maps. The system is equipped with a geofencing feature, defined as a virtual boundary used to determine whether an elephant is located within or outside a designated safe area. When the elephant crosses the predefined geofence boundary, the system automatically generates an early warning notification for authorized personnel or relevant stakeholders.

2.2. Electronics Design

2.2.1. GPS Devices

The GPS tracking device is illustrated in Figure 2. The GPS module functions to acquire geographic coordinate data, specifically latitude and longitude, from satellite signals. The positional data obtained by the GPS module are then transmitted to the TTGO ESP32 via serial communication. The TTGO ESP32 serves as the primary microcontroller, responsible for processing the GPS data and preparing them for transmission to the gateway device. In addition to functioning as the main controller, the board is equipped with an integrated LoRa wireless communication module, enabling efficient long-range data transmission. A battery component provides the power supply for the entire system, allowing the device to operate autonomously in field conditions without requiring an external power source. The battery type used in this device is a 18650 lithium-ion battery, which supports stable and portable operation for outdoor deployment.

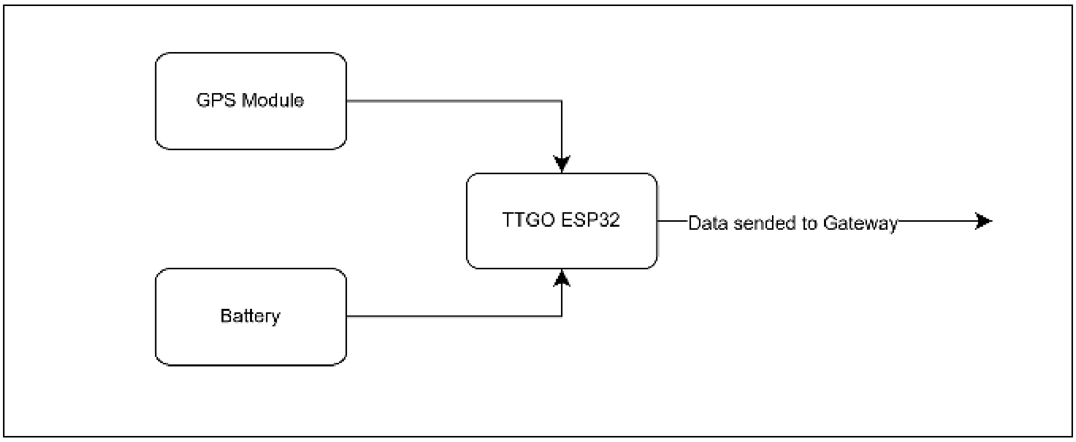

Figure 2. Blok Diagram of GPS Devices

2.2.2. LoRa Devices

The LoRa gateway device used in this system is illustrated in Figure 3. Location data transmitted from the GPS tracking device are received by the TTGO ESP32. The microcontroller then processes the received data and forwards them to the central server using the MQTT protocol, which is well-suited for efficient IoT data communication. A battery serves as the power source, enabling the gateway system to operate independently without reliance on external electrical infrastructure. The battery type used in the LoRa gateway device is the same as that used in the GPS tracking device, namely a 18650 lithium-ion battery, ensuring consistent power configuration across system components.

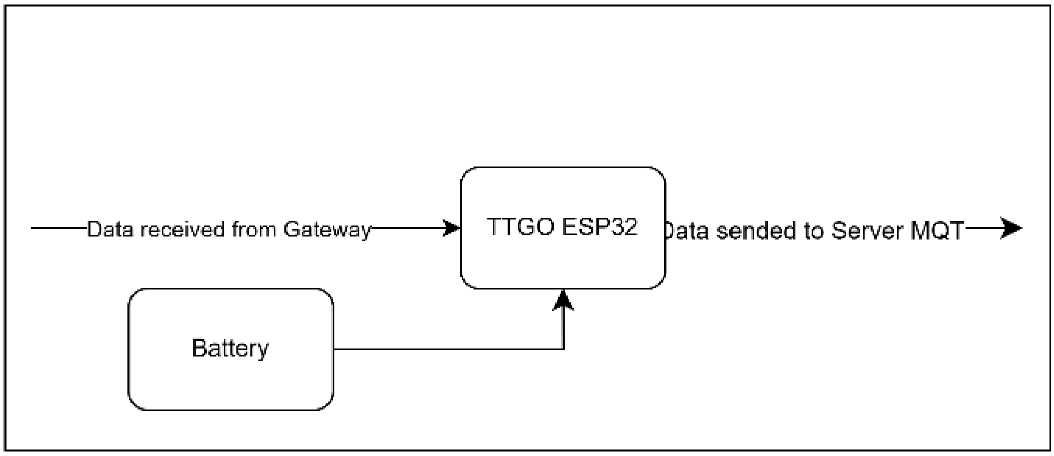

Figure 3. Blok Diagram Of Gateway

2.3. Dashboard Design

2.3.1. Backend

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The backend constitutes the system component responsible for processing data transmitted by the LoRa gateway device. In this study, the backend is developed using the Python programming language with the Django framework. The selection of Python is based on its readability, extensive ecosystem of supporting libraries, and ease of integration with various systems. Furthermore, Django provides a well-structured and secure architecture for data management, as well as efficient communication with the server and database. This framework facilitates the development of scalable web services and Application Programming Interfaces (APIs) required for real-time monitoring and data visualization.

2.3.2. Frontend

The frontend represents the system component responsible for presenting processed data from the backend to end users. In this study, the frontend is developed using the React framework. This framework is selected due to its lightweight architecture, interactive capabilities, and support for dynamic and responsive user interfaces. Through the frontend application, users can monitor elephant positions in real time, observe movement status updates, and receive early warning notifications when elephants cross predefined geofence boundaries. The interactive interface enhances situational awareness and enables timely decision-making for conservation personnel and relevant stakeholders.

2.3.3. Database

The database component is utilized to store all monitoring data, including location coordinates, timestamps, and device identifiers. This system employs PostgreSQL as the primary database management system due to its capability to handle large-scale datasets and its support for spatial data types required for processing geographic coordinates. The database is directly integrated with the backend, ensuring that each data packet received from the gateway is stored systematically and made accessible to the frontend in real time. This architecture enables efficient data retrieval, spatial analysis, and visualization to support continuous monitoring and early warning functionalities within the system.

2.3.4. Geofence

Geofencing is a method used to determine whether a specific geographic position (longitude and latitude) lies within a predefined area. In this study, the geofencing mechanism is implemented to evaluate whether the positional data transmitted from the tracking node are located within a designated residential or restricted zone. If the node (elephant) is detected within the defined area, the system automatically generates an early warning notification delivered through the Telegram platform. Telegram is selected due to its open-source ecosystem, widespread adoption, and support for bot-based automated notification services. The following pseudocode describes the proposed geofencing algorithm.

```
Function check_geofence(lat1, lon1, lat2, lon2, radius_km):
   R ← 6371

   dlat ← radians(lat2 - lat1)
   dlon ← radians(lon2 - lon1)

   a ← sin(dlat / 2)^2 + cos(radians(lat1)) * cos(radians(lat2)) * sin(dlon / 2)^2
   c ← 2 * atan2( sqrt(a), sqrt(1 - a) )

   distance ← R * c

   IF distance ≤ radius_km THEN
      inside ← TRUE
      send notif
   ELSE
      inside ← FALSE
   END IF

   RETURN (inside, distance)
END FUNCTION
```

3. RESULTS AND DISCUSSION

3.1. MQTT Latency

MQTT latency was measured to determine the time required for data transmitted from the gateway to reach the server via the MQTT protocol. Latency measurement is essential to evaluate the responsiveness and reliability of the communication system, particularly for real-time monitoring and early warning applications. Figure 4 presents the latency graph of data transmission from the gateway to the server. The results illustrate the communication performance of the proposed system under the tested network conditions.

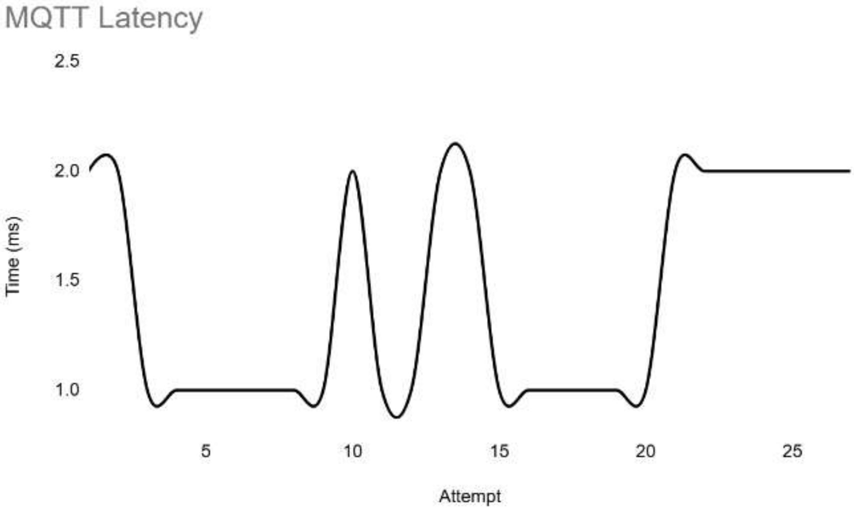

Figure 4. MQTT Latency

Based on the obtained data, the average time required to transmit data from the gateway to the server using the MQTT protocol is 1.44 ms, indicating that the data transmission process is both rapid and stable. This low latency value demonstrates that the proposed system achieves efficient communication performance with a favorable response time. Such performance is particularly advantageous for real-time monitoring and early warning applications, where minimal transmission delay is critical to ensuring timely decision-making and effective mitigation actions.

3.2. Notification Latency

The early warning latency was measured based on the total time required to perform the geofence computation and to transmit the alert notification to the Telegram platform. Figure 5 presents the graph illustrating the time required to execute the geofencing calculation and deliver the early warning notification.

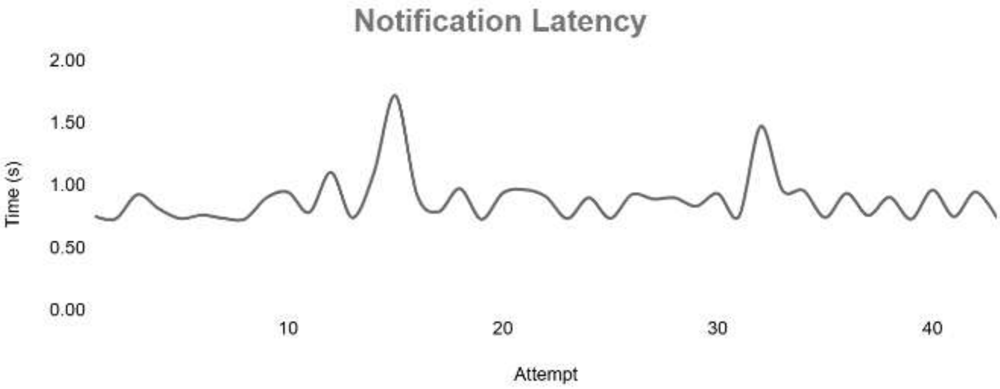

Figure 5. Notification Latency

Based on the experimental results, the system requires an average of 0.89 seconds to complete the geofence computation and transmit the notification. This finding indicates that the proposed system is capable of generating near real-time alerts, which is critical for enabling timely mitigation measures in potential human

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elephant conflict situations. Figure 6 shows the early warning notification interface displayed via Telegram, presenting the elephant's identifier and the specific area boundary that has been crossed.

Figure 6. Early Warning Notification

3.3. LoRa Testing

The LoRa communication range testing was conducted in an open-area environment with minimal obstacles, such as high-rise buildings and dense vegetation, in order to obtain optimal signal conditions. The range evaluation was carried out along Jalan Tengku Buang Asmara, as shown in Figure 7. This location was selected to ensure line-of-sight (LoS) conditions and to accurately assess the maximum achievable communication distance of the proposed LoRa-based monitoring system.

Figure 7. Range Testing Location

This experiment was also conducted to obtain the Received Signal Strength Indicator (RSSI) value at each measured distance. RSSI measurements are essential for evaluating signal quality and communication reliability as the transmission distance increases. Table 1 and Figure 8 present the tabulated data and graphical comparison between transmission distance and the corresponding RSSI values obtained during testing. These results provide insight into the signal attenuation characteristics of the proposed LoRa-based monitoring system under open-area conditions.

Table 1. RSSI and Distance

No	RSSI (dB)	Distance (m)
1	-85	651.6959158
2	-87	663.9998496
3	-98	684.7130142
4	-93	728.3596503
5	-96	737.6932745
6	-99	756.3553546
7	-100	769.0450684
8	-104	779.3507352
9	-101	779.5920528
10	-99	786.8929714
11	-102	814.3060838
12	-104	827.1336534
13	-98	838.4887197
14	-105	875.7266
15	-104	894.5758438
16	-102	905.6944512
17	-105	960.0497581
18	-105	960.504103
29	-105	999.0445176
20	-105	1012.3887

Based on the conducted experiments, the maximum communication distance achieved was 1,012 m (approximately 1 km), with a corresponding RSSI value of −105 dB. These two parameters exhibit an inverse relationship: as the transmission distance decreases, the RSSI value increases (i.e., becomes less negative), and vice versa. This behavior is consistent with the fundamental characteristics of wireless signal propagation, where signal strength attenuates as distance increases. The obtained results demonstrate the capability of LoRa technology to support reliable direct (peer-to-peer) data transmission over long distances, making it suitable for wide-area wildlife monitoring applications.

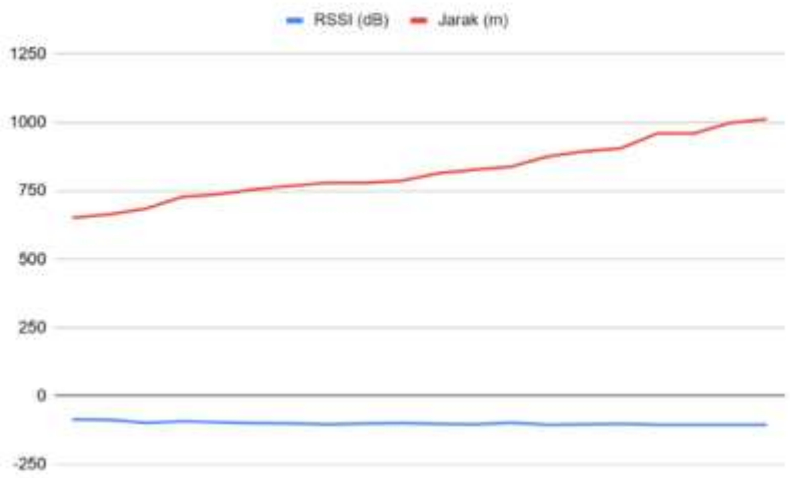

Figure 8. RSSI and Distance Comparation

3.4. Dashboard

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The following presents the dashboard interface of the proposed elephant monitoring system, which incorporates several key features, including:

3.4.1. Maps Visualization

This feature enables the visualization of the elephant's position on a digital map, allowing users to easily identify the current geographic location of the monitored elephant. Such visualization enhances situational awareness and supports rapid decision-making in the field. Figure 9 illustrates the map-based visualization of the elephant's position.

Figure 9. Elephant Posisition Visualization

3.4.2. Elephant Movement Visualization

This feature enables users to review the historical movement or positional data of the elephant over a specified time period, such as the last 24 hours. By accessing this functionality, users can analyze movement patterns and evaluate spatial behavior within a defined timeframe. Figure 10 illustrates the visualization of the elephant's movement trajectory, which is also complemented by a graphical representation of the distance between the elephant and the gateway. This additional information provides insight into communication range performance and spatial distribution relative to the gateway location.

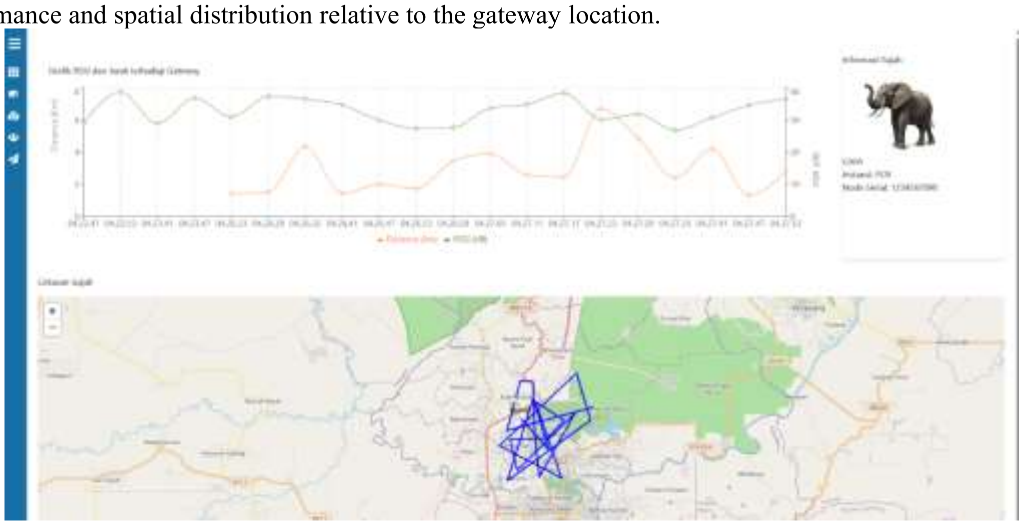

Figure 10. Elephant Movement Visualization

4. CONCLUSION

The experimental results demonstrate that the proposed LoRa-based monitoring system operates with low communication latency and stable data transmission performance. The average data transmission time from the gateway to the server using the MQTT protocol was 1.44 ms, indicating an efficient backend communication process. Additionally, the average notification delivery time to end users was 0.89 seconds, which is acceptable for near real-time IoT-based early warning applications. Communication testing showed that the system maintained stable connectivity at distances up to 1 km, with an RSSI value of −105 dB, confirming reliable performance within the tested range. Regarding the geofencing mechanism, functional testing confirmed that the radius-based boundary detection algorithm successfully identified simulated boundary crossings and triggered automated warning notifications accordingly. The system was able to differentiate between positions inside and outside the predefined virtual boundary based on calculated distance thresholds. This demonstrates the feasibility of integrating geofence-based early warning within a LoRa communication framework.

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