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RESEARCH ARTICLE

A Scalable and Energy-Efficient LoRaWAN-Based Geofencing System for Remote Monitoring of Vulnerable Communities

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ABSTRACT With the advent of the Internet of Things (IoT), Long-range Wide Area Networks (LoRaWAN), and high-speed internet, the potential to use such technologies for monitoring remote areas with limited cellular coverage is becoming increasingly important. However, existing remote monitoring solutions rely on cellular networks, which often do not exist or are unreliable in remote communities such as oil & gas and mining sites, livestock farms, and some specialized care clinics for monitoring individuals with Alzheimer's disease. Furthermore, existing LoRa-based systems that are geolocation aware used star network topology, which has been proven to be not scalable to cover remote communities due to maintaining a massive volume of routing tables. This paper introduces a LoRaWAN-based geofencing system designed to address the unique challenges faced by these communities, especially areas with limited cellular coverage. The proposed system uses an optimized version of the Echo protocol to enhance the system's reliability, which runs over a mesh network topology that provides a scalable solution for monitoring remote areas. In particular, we developed a geolocation and geofencing alert system tailored to overcome the limitations of cellular coverage in remote areas. Our system utilized LoRaWAN hardware supported by an optimized Echo protocol in a zero-control mesh network to efficiently detect boundary breaches of the monitored subjects such as cattle, patients with Alzheimer's disease, robots mounted with IoT devices and sensors, etc. Experimental results showed that our system outperformed cellular-based systems regarding energy efficiency and scalability.

INDEX TERMS Remote monitoring, LoRa, LoRaWAN, geofencing, scalability, energy efficiency, IoT.

I. INTRODUCTION

The unique needs of remote and vulnerable communities in global safety infrastructure, coupled with the limitations of existing cellular-based monitoring systems, underscore the necessity for novel approaches that address these challenges [1], [2]. In addition, the widespread use of monitoring devices across many remote locations consumes significant power for such devices, which are often battery-dependent [3], leaving substantial gaps in safety measures. To bridge these gaps, there is a persistent need for an energy-efficient, reliable, and scalable approach for real-time monitoring of these target areas.

Traditional monitoring methods often rely on cellular networks, which still need to be more present and reliable in remote areas [4]. One way to address this challenge is using Long-range Wide Area Networks (LoRaWAN) that do not require Internet connectivity while operating independently. LoRaWAN is a Low-Power Wide Area Network (LPWAN) technology [5] that offers wide-area coverage to low-power Internet of Things (IoT) monitoring devices. LoRAWAN is suitable for long-distance, low-power

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consumption, low-bandwidth, and multi-connection IoT devices, especially in remote vulnerable communities [6].

This paper presents a scalable and energy-efficient LoRaWAN-based geofencing system for remote monitoring of vulnerable communities. The proposed system – characterized by cost-effective LoRa nodes, presents a financially accessible alternative to cellular-based systems– offers a proactive solution in remote monitoring of remote communities. In addition, the superior energy efficiency of LoRa technology over GSM-based systems boosts its suitability for long-lived continual tracking [7].

Our system employs a zero-control mesh network supported by an optimized Echo protocol [8], –initially proposed for Mobile Ad Hoc Networks (MANETs) [9]– as an underlying that offers an efficient solution for real-time remote monitoring. ECHO eliminates the need for conventional routing tables, thus enhancing the system's reliability and scalability. However, when deployed in the IoT domain, the ECHO protocol suffers from degraded network performance. Therefore, We extended and ported the ECHO protocol to the IoT domain by mitigating high collision rates, which degrades the mesh network performance.

We addressed the challenge of high collision rates in the ECHO protocol in dense LoRaWAN networks by intelligently adapting the rebroadcast delay, thus effectively managing the network congestion. Our approach seeks to balance the inherent trade-offs between network reach, efficiency, and power consumption, making it a promising solution for enhancing LoRaWAN's capabilities in supporting more complex network structures like mesh networks. The proposed protocol also demonstrated improved energy efficiency, potentially increasing the battery lifespan of the IoT monitoring devices [10].

We built a map dashboard that allows users to track the target objects and draw out the geofencing areas, depicting boundaries by coordinates and markers to uniquely identify the specific geofencing regions using polygon and circle shapes. We conducted a set of real-world experiments using LoRa hardware to evaluate the effectiveness and efficiency of the proposed system using various network configurations.

A set of real-world experiments was conducted using LoRa hardware to evaluate the proposed system. Most notably, we found a significant decrease in the average Packet Collision Rate (PCR) from 20% to 10%, alongside an increase in Network Throughput (NT) from 80 to 90 packets per minute. In addition, our optimized routing protocol achieved a packet success rate of over 92% compared to 85% for the ECHO protocol, despite a marginal rise in average network latency.

The rest of the paper is organized as follows: Section II presents related work. Sections III and IV present the design and prototype implementation of the proposed system, respectively. Section V experimentally evaluates the system in terms of energy and cost efficiency packet, collision rate, and packet delivery ratio. Finally, Section VI summarizes the results of this work.

II. BACKGROUND AND RELATED WORK

A. ECHO PROTOCOL

Existing studies focusing on optimizing routing protocols in MANETs and LoRa networks have emphasized the significance of reducing overhead and enhancing network efficiency [11], [12]. The ECHO protocol [8] is designed to deliver messages across LoRa mesh network nodes efficiently. The protocol operates in two phases: the Full Flood (FF) and Pruned Flood (PF). An FF data packet is initiated to select the critical nodes in a network-wide broadcast route based on metrics, including the packet's origin, sender, previous sender, and a unique sequence number. An echo packet is sent to all selected critical nodes to construct the optimal broadcast route (i.e., backbone).

Once critical nodes are identified, the protocol transits into the PF phase, where only these nodes relay subsequent data packets, leading to more efficient network operation. PF mode reduces the volume of data transmissions compared to the FF mode, thus increasing network communication efficiency. FF mode can be initiated again only in response to significant topology changes, ensuring the current broadcast route is updated and reflective of the existing network structure. Echo aims to balance the need for network-wide reachability with the minimization of redundant transmissions, making it particularly effective in LoRa, where conserving bandwidth and energy is essential [13]. This approach also helps distribute the load across various nodes, promoting longer network life and stability.

Each node in ECHO has three states: Not critical, pending, and critical. Initially, all nodes are marked as not-critical state. Upon a not-critical node receives an FF packet, it retransmits a modified version of the FF packet by setting previous-sender field in the packet's header to its uniquer ID and marks itself as pending state. Once the next node receives an FF packet with the previous-sender field set, it is said that this node has heard an echo message and transits to the critical state. This critical status denotes that that node plays an essential role in the network's broadcasting backbone and is responsible for relaying further PF packets. However, if any FF packet does not meet this condition for a pre-configured timeout, then the node transits from a pending to a non-critical state again.

B. LoRA TECHNOLOGY

LoRa technology is a pivotal advancement in low-power wireless communication, particularly in the IoT domain [14]. LoRa's architecture is designed to enable long-range communication with minimal power consumption, making it ideal for applications in smart cities, agriculture, and environmental monitoring [15]. The critical characteristics of LoRa include its ability to operate over long distances, robustness to interference, and low data rate transmission, which are essential for battery-operated IoT devices [16]. However, the low data rate aspect of LoRa presents unique challenges in network protocol optimization, necessitating adaptations to the standard MANET protocols, such as the ECHO protocol, to operate efficiently in IoT [3].

Numerous advancements have been made in optimizing LoRa communication in literature. An adaptive spreading factor is a notable method in this optimization realm [14]. Implementing an adaptive spreading factor in LoRa communication is a significant stride towards tailoring network performance to the specific requirements of varying applications, ensuring both reliability and efficiency in data transmission [17]. Implementing private servers for LoRa communication and the subsequent data visualization represent critical facets of IoT. Such server frameworks offer enhanced control and security for LoRa-based networks, which is crucial for handling sensitive IoT data.

Additionally, integrating robust data visualization tools is indispensable for interpreting the vast volumes of data generated by IoT devices. This dual approach of private server implementation and sophisticated data visualization is pivotal in empowering IoT solutions, enabling efficient data management, insightful analytics, and informed decision-making. These developments underscore the backend infrastructure's growing sophistication and strategic importance in the IoT ecosystem. This adaptive mechanism aligns with the evolving needs of sophisticated wireless communication systems, representing a pivotal development in low-power wide-area network technologies [5].

LoRa technologies excel in long-range coverage, reaching several kilometers under line-of-sight conditions. It is ideal for covering vast areas, particularly in rural or remote settings where traditional infrastructure might be sparse [18]. This characteristic proves invaluable for remote monitoring and public safety systems where timely response is crucial across a vast geographical expanse.

LoRa stands out for its deficient power consumption. It is ideal for remote monitoring applications with limited power sources or where minimizing energy usage is a priority. This is particularly crucial in deployments in remote or hard-to-reach areas where regular maintenance and battery replacement are challenging.

In the context of LoRaWAN mesh networks, existing work has explored various techniques to enhance data transmission efficiency while adhering to the inherent limitations of the LoRa technologies. These include adaptive data rate control [9], power management strategies [2], and the optimization of packet sizes and transmission intervals [19]. Such efforts demonstrate the ongoing pursuit of balancing efficiency, reliability, and regulatory compliance in low-data-rate wireless networks. This paper focuses on scalable and energy-efficient monitoring solutions for remote areas with limited cellular coverage.

LoRa devices work in a way that prioritizes low power consumption, allowing them to operate on batteries for extended periods [5]. This translates to minimized maintenance costs and reduced environmental impact, as frequent battery replacements are unnecessary, an essential requirement for remote monitoring in locations with limited access to power grids. Furthermore, LoRa systems readily adapt to varying deployment sizes, making them a cost-effective alternative to traditional cellular networks for large-scale sensor networks [20]. This scalability feature empowers public safety agencies to tailor their deployments to specific needs and budgets, ensuring efficient resource allocation without compromising coverage or response times.

LoRa is suitable for near real-time critical alerts, potentially leading to quicker emergency response times [4]. However, it is ineffective for high-bandwidth demanding applications because it operates on low-data networks [13]. Also, LoRa operates on unlicensed bands, making it susceptible to interference from other radio signals, potentially impacting reliability in congested environments [1]. LoRa networks are vulnerable to hacking and data security breaches like any other wireless system. Therefore, robust security measures are crucial for protecting transmitted sensitive information [10]. Also, compared to cellular networks, LoRa infrastructure is less established, especially in rural areas, posing challenges for initial deployment and maintenance [21].

C. EXISTING GEOFENCING EFFORTS IN REMOTE MONITORING USING LoRaWAN

LoRaWAN, an open system based on robust LoRa modulation, is highly suitable for rural coverage using low-power IoT devices. For instance, it has been used widely in agriculture, where it connects environmental IoT sensors for temperature and soil moisture with cloud servers [5], controls IoT actuators like irrigation valves [22], and supports tractor communications [4], livestock monitoring [23], and location tracing [24].

LoRaWAN can monitor livestock in real-time to ensure animal welfare, optimize resource allocation, and maximize productivity. However, traditional methods like manual observation or camera surveillance fall short in vast and remote ranches where cellular & GSM coverage is absent, leaving ranchers blind to the well-being of their animals [23]. However, LoRaWAN-based solutions emerge as game-changers, offering real-time monitoring and a cost-effective alternative to their cellular counterparts [1].

LoRaWAN has been used for the early detection of health issues of livestock animals via real-time data on vital signs like temperature, heart rate, and movement patterns, allowing for prompt intervention and potentially preventing illness and mortality [23]. This can be achieved through strategically placed LoRaWAN sensors attached to collars or ear tags, transmitting data regularly to a central hub [18].

Given that cellular coverage often dwindles in remote areas, leaving large portions of grazing land unmonitored [1], [21], LoRaWAN is an alternative solution for such environments. Its impressive long-range coverage, which reaches several kilometers in line-of-sight conditions, effortlessly covers these expanses, ensuring comprehensive data acquisition [25]. Furthermore, LoRa infrastructure requires minimal investment compared to cellular networks, and the low power consumption of LoRa sensors translates to reduced operational costs over time [17]. This starkly contrasts cellular solutions, known for draining batteries quickly due to higher power requirements [2].

Most existing LoRaWAN solutions rely on a conventional star topology, where LoRa nodes transmit data packets directly to a central hub in the core of the LoRa network [5]. However, star topology is inefficient in continual monitoring due to maintaining massive routing tables, especially in vast area coverage. Also, adding more hubs to extend coverage can be expensive and impractical [19]. Alternatively, mesh topology using dual radio (i.e., Frequency-Shift Keying (FSK) scheme) has been used for an optimal balance of energy, bandwidth, and long-range in remote monitoring [6].

In the LoRaWAN mesh network, LoRa nodes are connected to each other and not necessarily connected to a LoRa hub. As a result, it eliminates any blind spots in the network and ensures comprehensive coverage across vast distances. Mesh topology enhances scalability by adding more nodes to the network that seamlessly extends coverage without additional hubs or complex infrastructure changes [13]. Also, mesh-based networks are resilient to outages even when some nodes malfunction or encounter obstacles; the mesh can reroute data across the network from different routes, maintaining overall network connectivity and data flow [12].

Geofencing technology, often implemented through smartphone apps, has gained popularity to define virtual boundaries and trigger alerts when target subjects cross them. For instance, Caregivers of dementia patients can set up geofences around specific areas, such as patients' homes or care facilities, and receive notifications when a patient enters or leaves these target areas via mobile apps. While geofencing coupled with mobile apps provides a user-friendly solution to remote monitoring, they rely heavily on the subject carrying a smartphone or wearable device. Also, these solutions typically require ongoing cellular data.

The limitations above, including the need for ongoing connectivity subscriptions, reliance on cellular connectivity, long-range constraints, compliance issues, and reliance on individuals carrying specific devices, underscore the need for an innovative approach that addresses these challenges comprehensively [4]. A practical solution must provide real-time monitoring, timely alerts, and proactive measures to prevent wandering incidents while being accessible, user-friendly, and cost-effective. Additionally, the solution should overcome challenges such as signal limitations in indoor environments and the resistance of individuals with cognitive disorders to wearing or carrying devices.

This paper introduces an approach that addresses these needs by leveraging low-power, long-range, zero-control mesh routing protocol combined with geolocation and geofencing alerts. By capitalizing on emerging technologies (e.g., LoRaWAN [5]) and the robust mesh network architecture, this approach aims to provide a reliable, accessible, and proactive means of preventing and responding to wandering incidents.

III. DESIGN

A. OPTIMIZED ECHO

The core premise of our optimization strategy for the ECHO protocol in LoRa networks hinges on the deliberate delay increase before the packets re-broadcasting. This modification is grounded in the inherent characteristics of LoRa technology, particularly its low data rate and long-range communication capabilities [20]. In low data-rate networks, the time window for potential packet collisions is proportionally larger due to the extended duration of each transmission.

By strategically increasing the re-broadcast delay, our approach aims to stagger the transmission instances of different nodes, thereby reducing the likelihood of simultaneous packet transmissions that lead to collisions. This optimization draws inspiration from the principles outlined by Gupta and Kumar [17], who demonstrated that controlled transmission delays can effectively decrease collision rates and enhance network throughput. Furthermore, extending the re-broadcast delay allows nodes more time to receive echo messages from neighboring nodes, thus reducing redundant transmissions and optimizing the utilization of the network's limited bandwidth.

The impact of increasing the re-broadcast delay in the ECHO protocol extends to two pivotal aspects of network performance: network efficiency and collision rates. From an efficiency standpoint, the proposed modification is expected to reduce the overall number of transmissions required to disseminate a packet across the network. This reduction is attributable to decreased collision-induced re-transmissions and more judicious use of airtime [14]. Regarding collision rates, our approach leverages the extended delay to mitigate the frequency of packet collisions. Collisions in wireless networks, especially in low data rate environments like LoRaWAN, can significantly degrade network performance and reliability. Our protocol fosters a more harmonious and collision-averse communication environment by ensuring nodes have a lower probability of transmitting simultaneously. As a result, it enhances the likelihood of successful packet delivery, thereby contributing to the robustness and reliability of the network.

Our protocol's design and implementation are founded on comparative analysis and hypothesizing the efficacy of an increased rebroadcast delay in reducing collision rates and enhancing network throughput. As shown in Algorithm 1, we altered the `ScheduleRebroadcast` procedure to increase the delay by adding an extra delay parameter, and `HeardEcho` procedure to extend the echo detection process for accommodating the increased delay. This means that nodes will listen for an echo message over an extended period, ensuring they don't rebroadcast if another node has already done so.

As shown in Algorithm 1, the rebroadcast delay is dynamically adjusted based on network conditions, explicitly targeting the efficient management of the "on the air" has been kept under 400 ms and the "dwell time" restrictions for LoRaWAN in the US902-928 band [8]. Also, the maximum rebroadcast delay is adjusted and recalculated from the original parameters to enhance network performance. This re-calibration aimed to minimize packet collisions while adhering to regulatory "on the air" time constraints. The updated maximum delay, applied within the optimized protocol, is designed to improve transmission efficiency and reduce network congestion, thereby supporting more reliable and sustainable communication within the constraints of LoRa's low-data-rate environment.

The transmission time of each data packet, T_{packet}, can be calculated as:

$$T_{\text{packet}} = \frac{\text{Packet Size (in bits)}}{\text{Data Rate (bps)}} = \frac{320}{5000} = 64\text{ms} \quad (1)$$

In the original ECHO protocol, the average rebroadcast delay was set to 50ms, and the average collision rate was measured to be 20% based on empirical data derived from preliminary experiments conducted on the ECHO protocol, as shown in Figure 8. In particular, we conducted several experiments of the ECHO protocol under standard operating conditions to gauge the network's collision rate accurately. Therefore, the observed 20% collision rate reflects the probability of packet collisions occurring during transmission over wireless channels. This empirical approach provides a solid foundation for our protocol optimization strategies. Specifically, the data obtained from these experiments are instrumental in configuring our enhanced ECHO protocol's adaptive rebroadcast timing mechanism. By understanding the inherent collision dynamics within the network, we can tailor the rebroadcast delay to minimize the likelihood of further collisions, thereby optimizing overall transmission efficiency.

While a 20% collision rate may initially appear high, it is common in densely populated network environments where multiple devices transmit data concurrently. Our findings underscore the critical need for intelligent protocol adaptation in such scenarios to ensure reliable and efficient communication. The intelligent adaptation mechanism we've integrated into the ECHO protocol is designed to dynamically adjust rebroadcast delays based on real-time network conditions, including the observed collision rate.

Algorithm 1 A Pseudocode of the Proposed Optimized Location-Unaware Protocol for LoRaWAN Mesh Networks

```
Global Variables:
    baseDelay ← 50                    ▷ Base delay in milliseconds
    maxDelay ← 323.2                  ▷ Maximum delay in milliseconds
    collisionCount ← 0                ▷ Count of collided packets
    lostPacketCount ← 0               ▷ Count of lost packets
procedure Initialize
    knownTopology ← False
    isPartOfBackbone ← False
    collisionCount ← 0
    lostPacketCount ← 0
procedure Broadcast(packet)
    Send packet with unique identifier
    currentDelay ← baseDelay
procedure OnReceive(packet)
    if isNew(packet) then
        ScheduleRebroadcast(packet, currentDelay)
        UpdateDelay
    else if isRetransmission(packet) then
        collisionCount ← collisionCount + 1
procedure ScheduleRebroadcast(packet, delay)
    Wait for delay
    if not HeardEcho(packet) then
        Rebroadcast(packet)
    else
        lostPacketCount ← lostPacketCount + 1
procedure UpdateDelay
    while currentDelay ≤ maxDelay do
        currentDelay ← min(currentDelay + 1, maxDelay)
procedure HeardEcho(packet)
    Listen for packet rebroadcast by other nodes
    if heard then
        return True
    else
        return False
```

This approach allows for a more responsive and efficient handling of packet transmissions, significantly enhancing the protocol's performance in diverse and variable network environments. We appreciate the opportunity to elucidate these aspects of our research further and hope this explanation addresses the concerns raised. Our findings contribute to the ongoing dialogue on optimizing wireless communication protocols to meet the demands of increasingly complex network landscapes.

Therefore, the total collision time, $T_{\text{collision\_echo}}$, in ECHO can be calculated as follows:

$$\begin{aligned} T_{\text{collision}} &= T_{\text{packet}} \times \text{Collision\_Rate} \\ &= 64 \times 0.2 \\ &= 12.8\text{ms} \end{aligned} \quad (2)$$

The "on the air" time parameter, T_{echo}, in ECHO consists of the sum of the packet transmission time and the time added due to re-transmissions caused by collisions, which can be calculated as:

$$\begin{aligned} T_{\text{On\_Air}} &= T_{\text{packet}} + T_{\text{collision}} \\ &= 64 + 12.8 \\ &= 76.8\text{ms} \end{aligned} \tag{3}$$

The max re-broadcast delay in our protocol, T_{maxDelay}, can be calculated as the maximum dwell time for the LoRA mesh in the USA subtract $T_{\text{On\_Air}}$:

$$T_{\text{maxDelay}} = 400 - 76.8 = 323.2\text{ms} \tag{4}$$

B. LoRaWAN-BASED GEOFENCING SYSTEM

Figure 1 shows the distributed runtime system for the proposed LoRaWAN-based geofencing system for remote monitoring, organized with parts executing on the LoRa nodes and hubs at the remote monitoring sites, on remote servers at the cloud side, and users' computers and mobile devices at the user side.

On the remote monitoring side, the LoRaWAN mesh network monitors remote areas. It offers self-forming, self-healing capabilities and a resilient multi-hop network suitable for dynamic scenarios where LoRa nodes are mobile and the network topology changes frequently. It provides real-time insights into the target subjects' location and behavior, even where cellular networks falter, across various domains, including health care, agriculture, entertainment, environmental monitoring, transportation, etc. [6].

For instance, this system can be used in precision and smart agriculture to empower farmers to optimize land management, improve animal welfare, and boost productivity while remaining cost-effective and resilient to infrastructure challenges, especially in the world's remotest corners. Data is collected from various LoRa and IoT nodes, including soil moisture, temperature, wind speed and direction, solar radiation, leaks monitoring, accelerometer, GPS, proximity, motion, dew point sensors, etc. IoT gateways are used to aggregate these sensing data and coordinate the connectivity of nodes to each other and to the cloud side. The gateway keeps aggregating the received sensor data until a sufficient number of them have been received to detect an interesting event, such as a change in the level of soil moisture in an agricultural field.

As shown in Figure 1, the communication between the remote monitoring, cloud, and user sides is carried out through the Gatekeeper, which implements various security mechanisms to ensure the incoming messages are legitimate. The end-users (e.g., farmers and healthcare providers) and researchers can utilize the proposed monitoring system using web-based tools and mobile apps from their computing devices such as PCs and Smartphones. The user interface will help users remotely operate the system to conveniently access the sensing devices on their agricultural fields or patients. It eliminates the need for constant manual monitoring of the monitored areas. This design provides cost-effective and optimal solutions to users with minimal manual intervention.

We implemented an optimized Echo protocol to facilitate seamless communication among LoRa nodes, as discussed in Section III-A. This protocol is specifically designed to maximize communication between low-power IoT and LoRa devices, ensuring efficient data exchange and energy conservation. This energy-efficient approach plays a crucial role in the performance of our system, allowing for prolonged operation without the need for frequent battery replacements or recharging.

IV. IMPLEMENTATION

We have prototyped our optimized routing protocol and remote monitoring system using a real-world testbed implementing a mesh LoRaWAN in IoT settings. The testbed comprises two key components: (a) the identification of critical nodes through a single flood; and (b) the efficient management of comprehensive floods to refresh these critical nodes, accounting for any changes in the network topology.

A. PHYSICAL IMPLEMENTATION

Our experimental setup comprises two pivotal components: a central root LoRa node and a LoRa End Device (ED). First, the root node is equipped with a LoRa HopeRF 95w transceiver and an ESP32 microcontroller attached to a computer server, as shown in Figure 2. Its primary function involves establishing communication channels with a designated private server facilitated by the MQTT protocol over WiFi connectivity. It acts as the data processing and distribution hub within our monitoring system.

Second, the LoRa ED (shown in Figure 3) is a versatile unit that boasts comparable components, including a LoRa HopeRF 95w transceiver, an ESP32 microcontroller mounted on a breadboard, several jumper wires, and a GPS receiver. Each ED, leveraging its GPS receiver, can determine its precise location in real time, which is then efficiently transmitted to the central root node via the LoRa transceiver. The central root node, well-connected to the internet through WiFi, subsequently serves as the conduit for forwarding this location information to a designated private server. The server node processes the incoming data and visualizes it on a map in real time. This visualization aspect is crucial, enabling users to track and monitor the movement and location of all EDs in our remote monitoring system, effectively providing Geofencing capabilities.

We used a NEO-6M TTL GPS module equipped with EPROM by u-blox [26], capable of receiving signals from 22 GPS satellites, to acquire the target subjects' most accurate positioning information (i.e., latitude, longitude, and altitude). It includes a built-in 25×25mm active GPS antenna with a UART TTL socket that can also provide information on the time, speed, and heading direction of the LoRa node.

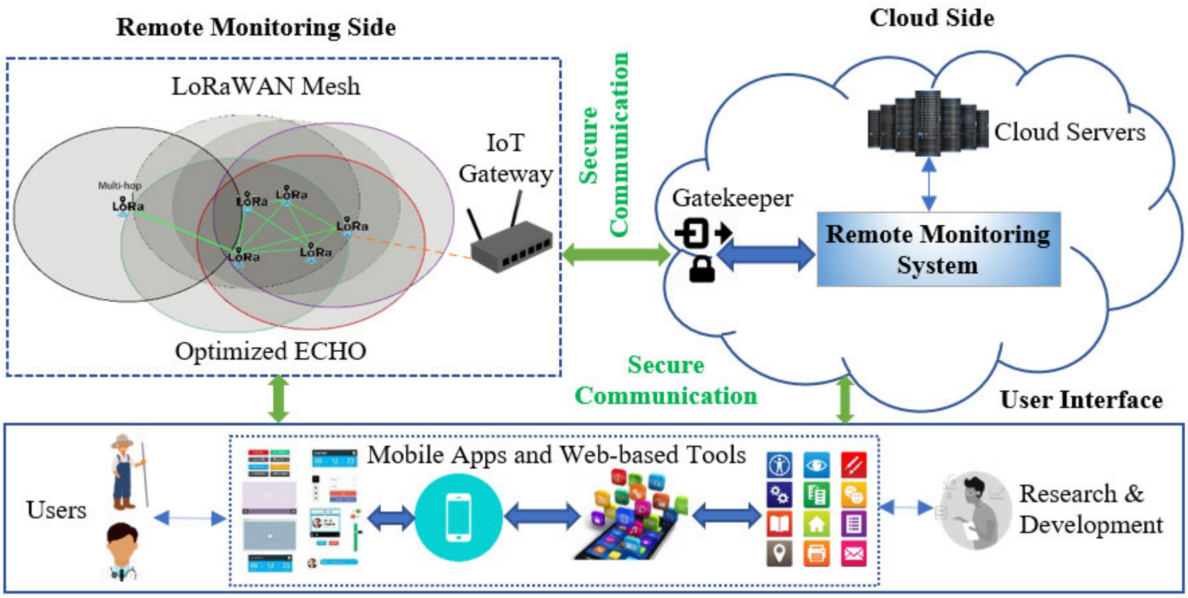


FIGURE 1. System architecture.

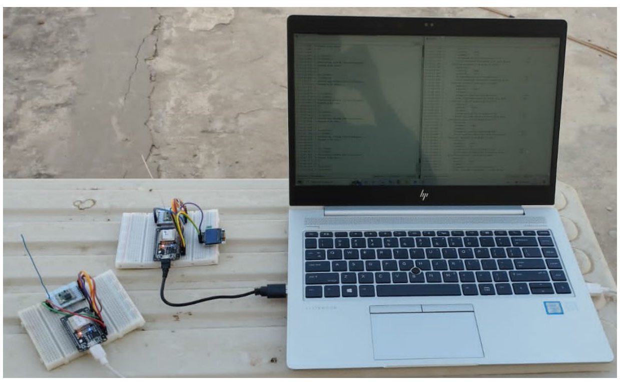


FIGURE 2. The central LoRa server used in the real-world testbed.

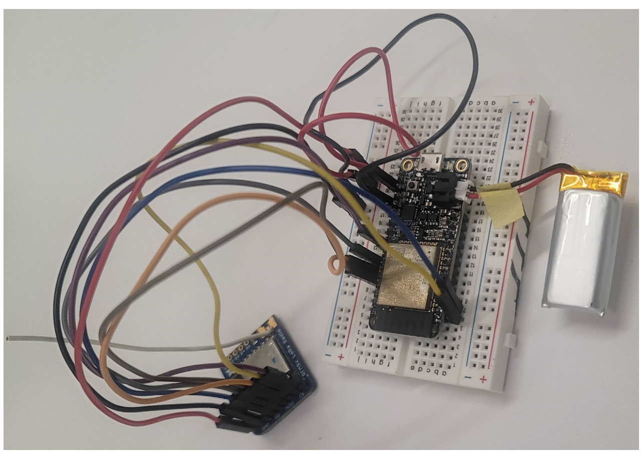


FIGURE 3. The hardware design of a LoRa end device.

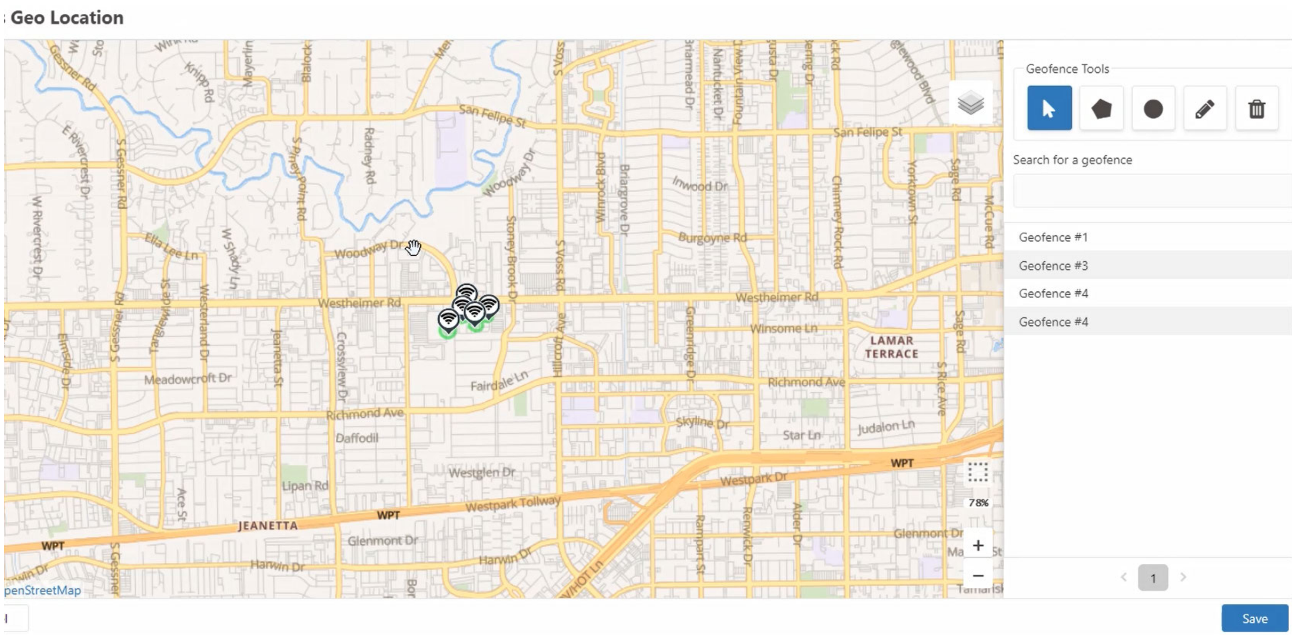
Also, we developed and installed software scripts written in C programming language to run on the ESP32 micro-controllers. These scripts operate diverse functionalities, including communication with LoRa radio, WiFi connectivity, GPS signal processing, and the transmission of data packets to a designated receiver LoRa hub. The optimized routing protocol was implemented in C programming language using a serial monitor. It is then uploaded and installed on the ESP32 Arduino Core (Version 2.03) via a micro-USB cable.

```
const geolib = require('geolib');

const point = { latitude: 29.737037, longitude: -95.509066 }
const geofence = [
  { latitude: 29.738, longitude: -95.510 }, // Point 1
  { latitude: 29.739, longitude: -95.509 }, // Point 2
  { latitude: 29.7385, longitude: -95.508 }, // Point 3
  { latitude: 29.7365, longitude: -95.508 }, // Point 4
  { latitude: 29.736, longitude: -95.509 },  // Point 5
];

if (geolib.isPointInside(point, geofence)) {
  console.log('Point is inside the geofence');
} else {
  console.log('Point is outside the geofence');
}
```

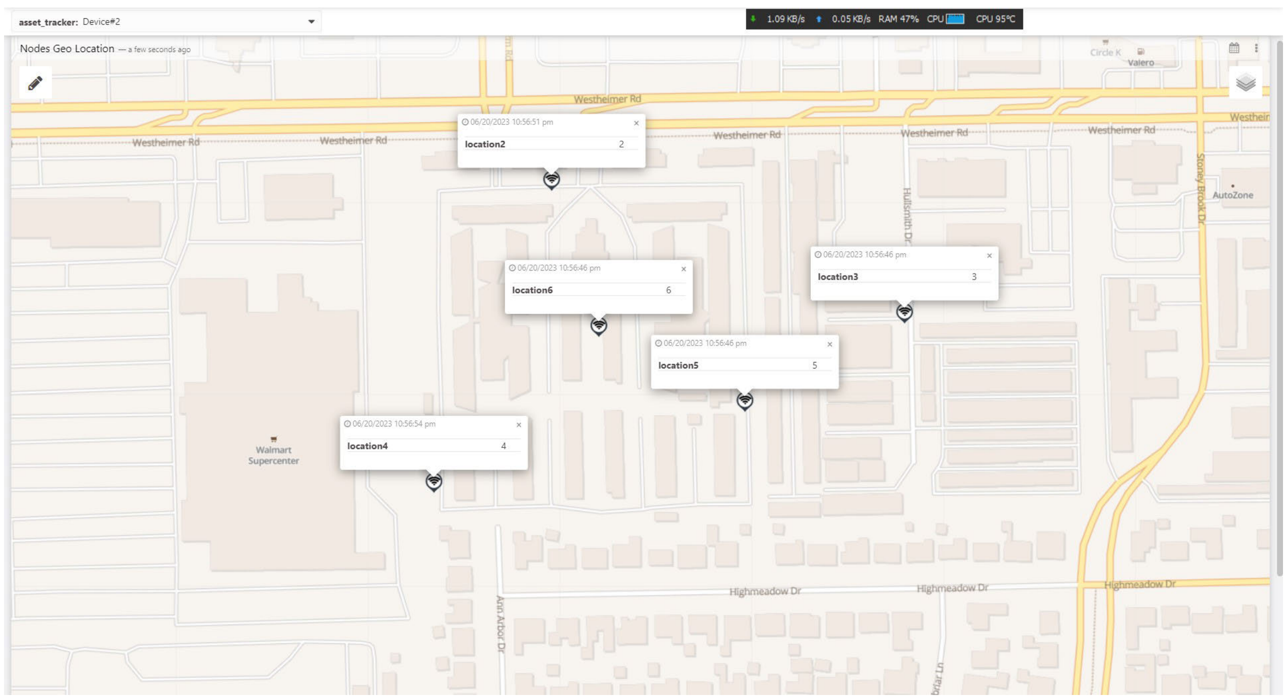
FIGURE 4. A JavaScript code defining a geofence polygon using Geolib library.

B. USER INTERFACE

The user interface is developed as a responsive, mobile-first, and user-friendly web application to enhance user experience using the system. We built the web application using Python



(a) The Web Application Dashboard



(b) Creating Five LoRa Nodes

FIGURE 5. Screenshots of the map-enabled web application.

Flask Framework, HTML5, CSS3, JavaScript, and JSON. All web pages are designed to be device-agnostic that can accommodate visitors using mobile devices, desktops, or televisions to visit the web site.

We developed a JavaScript codebase for parsing incoming messages from LoRa EDs. These messages encompass the EDs' locations and other monitoring parameters. The JavaScript code executes algorithms involving GPS coordinates and geofencing parameters, generating a value indicating whether the device is situated within or beyond the predefined geofenced area. When the device is identified as outside the geofence, our system transmits an MQTT message to the ED, instructing it to take further action.

We used Geolib, a versatile JavaScript library renowned for its utility functions for geographic coordinates and geometries. Geolib stands out for its lightweight architecture and user-friendly integration. It is valuable across various domains, including web and mobile development, Geographic Information Systems (GIS), and location-based services. Geolib is used to calculate the distance between two geographic points on a map precisely. It can be used to determine the bearing (i.e., direction) between two specified geographic locations and identify the midpoint between these two coordinates.

We used Geolib to establish the bounds of a set of geographic points and conduct proximity checks to ascertain whether a point is within a specified distance of a line or polygon. Also, it is used to execute fundamental geometry operations, such as locating the intersection point of two lines or determining the centroid of a polygon. As shown in Figure 4, we utilized the *isPointInside* utility function to assess whether a given location falls within a specified geofence polygon. In this context, a geofence represents a virtual boundary delineated around a geographic area.

Figure 5 shows the homepage of the map-based web application, which provides system users with a visualization panel for pinning LoRa EDs on the map and drawing monitoring zones around them. Using the MQTT protocol, our web application allows users to specify the EDs' speed information and capture the LoRa radio RSSI (Received Signal Strength Indicator) readings. Figure 5(a) shows the dashboard users can use to create new LoRa EDs and initiate the monitoring zones, which can be characterized as a circle or polygon. Figure 5(b) illustrates an example of creating five LoRa nodes close to the Greater Houston Area.

V. EVALUATION

We conducted a set of real-world experiments using LoRa hardware to evaluate the effectiveness and efficiency of the proposed system using various network configurations.

A. EXPERIMENTAL SETUP

Our experimental setup deployed five LoRa ED nodes, each equipped with LoRa ESP32 Arduino microcontroller, HopeRF 95w transceiver, Neo-6m GPS module, and batteries. Each node has an average communication range of approximately 2 miles, moving slowly to 4 miles/hr. By strategically positioning these five nodes, we established a network that effectively covers a radius of up to 10 miles during the 60 minutes of experiment duration. Table 1 shows the experimental parameters of our real-world testbed, which was conducted in the Greater Houston Area. The data rate and packet size were set to 5 Kbps and 40 Bytes, respectively. We varied the period of sending broadcast packets from 5 seconds to 12.5 minutes.

The Spreading Factor (SF) in LoRa technology adjusts the data rate, directly influencing the transmission range and power consumption. Higher SFs increase the range and robustness to interference at the cost of reduced data rate and increased airtime, leading to higher power consumption. Conversely, lower SFs, such as SF 7, offer higher data rates but reduced range and sensitivity. Our system's default SF was guided by the need to balance throughput with range and energy efficiency. SF 7, the lowest available SF, offers the highest data rate, making it an attractive option for maximizing throughput. This is particularly beneficial in environments where monitoring nodes are relatively close to each other or the gateway and where minimizing transmission time to conserve battery life is critical.

TABLE 1. Testbed experimental parameters.

Parameter	Value
Number of ED Nodes	5
Average Area Coverage	2 miles
Speed of ED Nodes	up to 4 miles/hr
Data Rate	5 Kbps
Packet Size	40 Bytes (payload and overhead)
Packet Interval	5 seconds - 12.5 minutes
Simulation Time	60 minutes

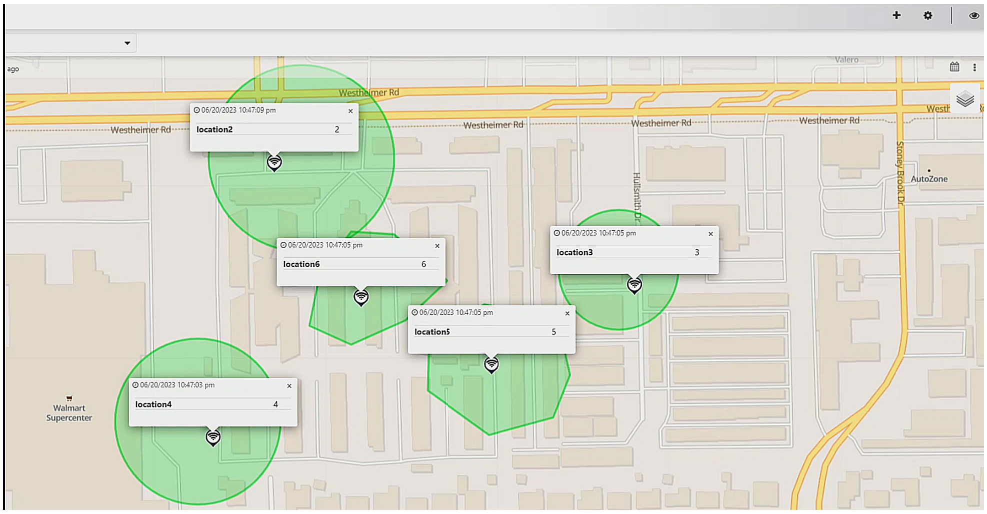
TABLE 2. Experimental results of the optimized routing protocol.

Metric	ECHO	Optimized Protocol
Collision Rate	20%	10%
Throughput (pkt/min)	40	50
Packet Delivery Rate	85%	92%
Battery Lifespan (hr)	48	52

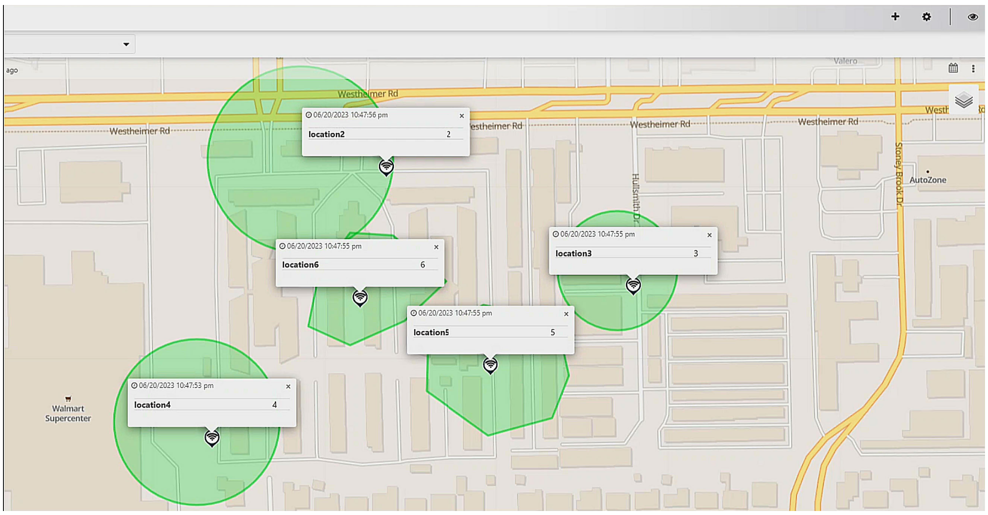
LoRa technology allows for different bandwidth settings: 125 kHz, 250 kHz, and 500 kHz. We used 125 kHz bandwidth in our experiments to provide sufficient range while maintaining a reasonable data rate, suitable for many remote monitoring applications that do not require high data throughput. The selected 125 kHz bandwidth also offers other benefits, including improved sensitivity, extended coverage range, energy efficiency, and the effectiveness of adaptive data rates.

Figure 6 shows screenshots of the monitoring scenario of the five EDs using the web application in different scenarios. As shown in Figure 6(a), we created five geofencing zones over the EDs using five different shapes, including circles and polygons. Implementing five distinct geofencing zones is designed to showcase the versatility and effectiveness of our optimized communication protocol within a mesh network context. These zones are carefully selected to represent a range of scenarios and applications from which our system could benefit. Each zone is connected via a mesh network, allowing end devices within these zones to communicate seamlessly using our optimized protocol. The choice of different geofencing shapes aimed to demonstrate the flexibility of our system to meet various user needs and preferences.

This flexibility is crucial for practical applications, as the nature of the monitored or controlled area can vary significantly. For instance, a circular geofence might be ideal for defining a straightforward boundary around a point of



(a) Creating Geofencing Zones over the Five Nodes



(b) Node # Two on the Move

(c) Node # Two Moved Outside the Monitoring Zone Triggering an Alert

FIGURE 6. Screenshots of monitoring the five EDs using the web application.

interest, such as a school or a retail store. In contrast, a polygonal geofence could be tailored to encompass irregularly shaped areas, such as agricultural fields or urban zones with complex boundaries. Regarding the resources or applications offered or provisioned within these geofenced zones, our system is designed to support a wide range of applications, from security and surveillance to environmental monitoring and smart city infrastructure management.

Our system can perform in-depth data analysis to trigger an alert when a node ventures beyond the predefined geofence boundaries. Figures 6(b) and 6(c) show an example scenario of node # 2 on the move departing the monitoring zone, triggering an alert with the latest monitored location of the node.

B. EXPERIMENTAL RESULTS

This section presents the experimental results of the real-world testbed presented in Section V-A.

1) EVALUATING THE OPTIMIZED ROUTING PROTOCOL

The empirical analysis conducted in this work utilized real-world LoRa hardware setups to assess the realm performance of our optimized protocol. Our experimental results demonstrated a substantial performance superiority of our optimized routing protocol compared to existing protocols such as ECHO in terms of Multi-Point Relay (MPR), flooding, and Opportunistic Announcement (OA).

As outlined in Table 2, when using ten LoRa EDs, the testbed experimental results showcased a 50% savings in battery life compared to ECHO while transmitting three times fewer packets. Further, the rate of successful packet delivery improved from 85% to 92%, albeit with a slight increase in average network latency.

Compared to ECHO, the optimized protocol achieved a 10% reduction in collision rate, a 10 pct per minute increase in the overall throughput, a 7% increase in PDR, and a 4-hour boost in the battery lifespan. This throughput improvement was achieved without violating the ''on the air'' restrictions inherent in LoRa networks, which is critical in maintaining regulatory compliance and operational efficiency.

These improvements underscore the pivotal role of avoiding explicit control packets in the FF phase, which minimized the overall communication complexity. It is also agnostic to specific MAC or Radio Frequency (RF) attributes and independent of traffic considerations. Therefore, our optimized protocol is scalable and supports a long lifespan of multi-hop LoRa mesh networks.

Figure 7 depicts a comparison between ECHO and our optimized protocol in terms of the average PDR when increasing the number of LoRa EDs from 4 to 10 while fixing all other parameters. As shown in the chart, our protocol achieved a significant enhancement of at least 30% in PDR, coupled with a substantial reduction in the overall communication load.

Figure 8 illustrates the Average Collision Rate (ACR) of our protocol compared to ECHO. As shown in the figure,

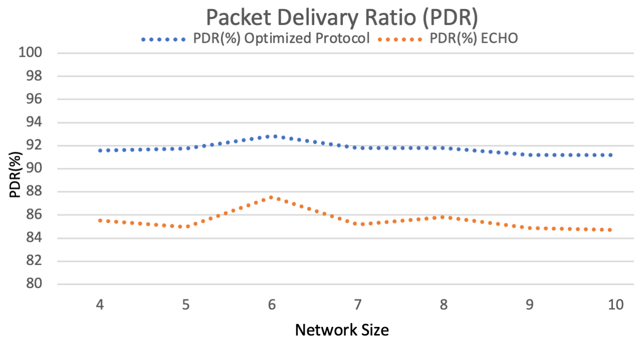


FIGURE 7. **The average PDR of the optimized routing protocol compared to ECHO.**

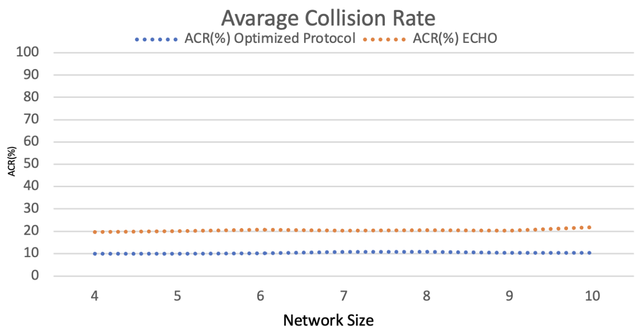


FIGURE 8. **The Average Collision Rate (ACR) of the optimized routing protocol compared to ECHO.**

we measured a notable decrease in ACR from 20% to 10%. This indicates that the optimized protocol can significantly mitigate higher collision rates in ECHO under the IoT settings.

Figures 7 and 8 present key QoS metrics directly influencing throughput and delay: the packet delivery ratio (PDR) and average collision rate. The packet delivery ratio is a crucial indicator of throughput efficiency, reflecting the reliability of our protocol in successfully transmitting data across the network. A higher PDR signifies more efficient throughput, demonstrating our protocol's effectiveness in managing network traffic to ensure successful packet delivery. Conversely, the average collision rate provides insight into network congestion levels, directly impacting communication delay. By showcasing a reduced collision rate, we emphasize our protocol's capability to minimize packet retransmissions and reduce overall network delay. Collectively, these metrics offer a nuanced understanding of our protocol's performance in balancing throughput and delay, which is pivotal for diverse application scenarios with varying QoS demands.

We developed an extended version of the ECHO protocol to work efficiently for LoRaWAN environments. This optimization is designed to maximize performance within the inherent dwell-time restrictions of LoRaWAN, ensuring efficient and reliable communication even under constrained conditions. ECHO, by nature, is highly scalable, making it well-suited for the expansive and diverse requirements

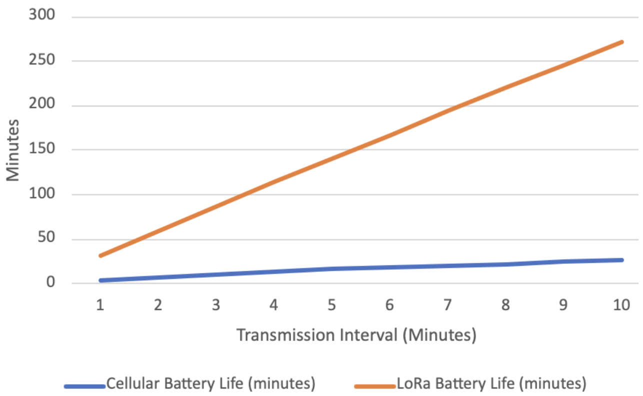


FIGURE 9. A comparison of the energy consumption of our LoRa EDs and cellular-based systems in terms of battery life.

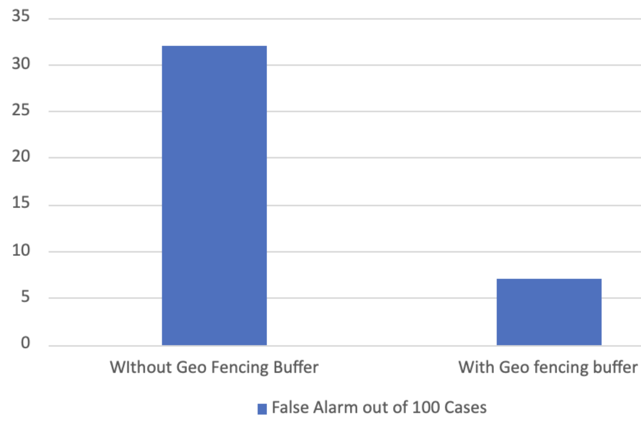


FIGURE 10. The effect of Geofencing buffer zones on triggering false alarms.

of LPWAN applications. It is important to emphasize that our experimental approach significantly differs from many studies in this field, which often rely on simulations to test their protocols. Instead, we have established a real-world testbed of up to 10 nodes. While seemingly modest in scale, this practical implementation was carefully chosen to provide a robust and realistic evaluation of our protocol's performance in actual operating conditions rather than theoretical or simulated environments.

Our experimental results from this real-world testbed have shown considerable promise. The data collected and the insights gained affirm our protocol's effectiveness and its potential for scalability across larger LPWAN deployments. The success of our protocol in a real-world environment, even with a limited number of nodes, is a strong indicator of its capacity to scale effectively, managing increased loads and larger network sizes without compromising performance. We understand the importance of scalability in the context of LPWAN and are committed to further research and testing to validate and continuously enhance our protocol's scalability. Our ongoing work will expand the testbed to include more nodes and explore diverse scenarios to rigorously assess the protocol's scalability and adaptability across a broader range of network sizes and configurations.

2) ENERGY CONSUMPTION

A set of experiments was carried out to measure the ongoing energy overheads of our system compared to the cellular-based monitoring systems. To accurately measure the lifetime of the batteries used in our experiments, we set the following parameters of our LoRa HopeRF 95w nodes: the duty cycle to 10% (0.10), active mode duration to 3 seconds, sleep time to 5 seconds, and the battery capacity to 400mAh. The battery life, Θ, is calculated as follows:

$$\Theta = \frac{\alpha}{(\gamma \times \tau) + (\delta \times \phi)} \tag{5}$$

where α is the battery capacity, γ is the active current, τ is the active time, δ is the sleep current, and ϕ is the sleep time.

Figure 9 depicts the performance of our system in terms of energy consumption of our LoRa HopeRF 95w nodes compared to the cellular-based alternative monitoring solutions. As shown in the figure, our system outperformed the cellular system significantly regarding battery lifetime. In particular, our nodes' batteries lasted 10X times more than the conventional cellular-based system using the same set of batteries. This shows that our monitoring system excels in energy efficiency, extending battery life for continuous remote monitoring.

Figure 9 shows another aspect of QoS by comparing the energy consumption of our EDs against that of traditional cellular-based systems, focusing on battery life as a critical metric. This comparison is vital, as energy efficiency directly correlates with the sustainable deployment of IoT devices in real-world scenarios, where extended battery life can significantly reduce maintenance costs and increase the viability of large-scale deployments. Including energy consumption analysis and throughput and delay metrics provides a holistic view of our protocol's performance and sustainability. By demonstrating competitive energy efficiency, coupled with robust throughput and minimized delay, our findings underscore the suitability of our optimized echo protocol for a wide array of applications within the LPWAN domain.

3) THE EFFECT OF GEOFENCING BUFFER ZONES ON TRIGGERING FALSE ALARMS

Creating buffer zones around geofences is a prudent strategy to mitigate inaccuracies in the ED's location information and GPS drifts. Therefore, we studied the effect of geofencing buffer zones on triggering false alarms in our monitoring system. Using buffer zones, our system ensures that alarms are only triggered when a device crosses the buffer zone and the primary geofence boundary.

We found that the buffer zones strategy enhanced the monitoring accuracy and reduced the false positive alerts by 450%. Figure 10 compares the number of false positive

TABLE 3. A cost comparison between LoRa EDs and cellular-based trackers.

Tracker Type	Yearly Average Cost	Lifetime Average Cost	Internet Requirement
LoRa ED	$20	$20	IoT Gateway and WiFi Technology
GPS-enabled Cellular Tracker (without subscription)	$250	$250	Requires GSM coverage
GPS-enabled Cellular Tracker (with subscription)	$360	∞	Requires GSM coverage

alarms using geofencing buffer areas and without using it. In particular, 32 false positive alarms were triggered out of 100 cases, compared to 7 instances when geofencing buffer areas were used.

4) COST EFFECTIVENESS MODEL

The cost-effectiveness model plays a crucial role in selecting remote monitoring technologies. LoRa-based systems require minimal investments to initiate and operate the network to monitor remote and vulnerable communities. In addition, it does not need periodic subscriptions to location-based cloud services compared to its cellular counterparts. Each ED used in our system costs on average $20, including the ESP32 board, LoRA RFM95, GPS module, and batteries. Conversely, the average cost of a cellular-based tracking unit is around $250, in addition to $30 monthly on average for a cellular subscription.

Table 3 compares the cost-effectiveness of our system and the existing cellular-based trackers in terms of the yearly and lifetime average costs. The conventional GPS-enabled cellular trackers require GSM coverage, whereas the LoRa-based EDs do not need it. We use a minimal-cost IoT gateway to provide internet connectivity to our mesh network using WiFi technology.

VI. DISCUSSION AND CONCLUSION

This paper presented a geofencing monitoring system that leverages LoRaWAN technologies to address the critical challenges in the existing cellular-based solutions efficiently. The proposed system could be utilized in various domains, including wild animal tracking, cattle monitoring, and individuals with cognitive impairments like dementia and Alzheimer's. Unlike cellular-based alternatives, our system offers a cost-effective, low-power, energy-efficient, and accessible solution for continuous and remote monitoring. Furthermore, the system's long-range capabilities provide reliable coverage indoors and outdoors. The proposed monitoring model revolutionizes the remote monitoring approach with its affordability, subscription-free model, and extended battery life, making it an accessible and cost-effective solution for caregivers and healthcare facilities. Its comprehensive coverage, independent of internet connectivity for individual devices, ensures reliable monitoring even in remote areas. Designed with a user-centric approach, our system offers real-time tracking capabilities and a friendly interface, empowering users with informed decision-making. This research underscores the proposed system's adaptability to diverse environments, offering a robust solution for safety and monitoring challenges in remote locations and specialized care scenarios.

The contributions of this paper are fourfold. First, we presented the design and implementation of a scalable and energy-efficient geofencing system for remote monitoring using a low-power, long-range zero control mesh LoRaWAN network. Second, this paper presented an optimized routing broadcast protocol for LoRaWAN Mesh networks that suits remote monitoring. The proposed protocol dynamically adjusts the rebroadcast delay in ECHO based on various network conditions, substantially decreasing network congestion and enhancing overall network throughput and reliability. Third, we presented a real-world testbed implementation and evaluation across diverse deployment scenarios that provided more profound insights into the system's performance under various conditions. Fourth, the system is evaluated extensively to assess its effectiveness and efficiency in a real-world environment, including indoor and outdoor settings. Experimental results showed that our system achieved a significant decrease in PCR and increased the packet success rate and network throughput compared to excising routing protocols.

In addition, this paper introduced the strategy of buffer zones around geofences, which significantly reduces false positive alarms, enhancing the system's accuracy and reliability. The experimental results substantially reduced false positives, making the system highly effective in real-world scenarios. The proposed optimized protocol also demonstrated enhanced energy efficiency, potentially increasing the battery lifespan of LoRa devices. While individual packet "on the air" time increased due to the prolonged rebroadcast delay, the overall network communication efficiency improved. In summary, the deployment of our protocol demonstrates significant enhancements in the reliability and efficiency of communications for low-data rate wireless networks such as IoT, underscoring the potential for broader application in analogous technological domains.

Incorporating analytical studies, including dynamic scenarios such as node mobility, stochastic data arrivals, and random traffic and collisions, could extend and evaluate our solution's scalability and performance under varying network conditions. However, for our specific case study focusing on the real-time testbed evaluation of the extended echo protocol, we believe that additional analytical studies, while informative, are not crucial for the following reasons: (i) The proven scalability of Echo protocol; (ii) The study focuses on real-world applicability that closely mimics actual deployment scenarios, providing direct insights into how the protocol performs in real-world environments; and (iii)

The efficiency of resource allocation focuses on tangible improvements and optimizations based on real-world data.

Beyond the technical improvements, our system's re-adaptability to the varying network conditions reflects a critical step forward in designing intelligent IoT systems, where IoT devices operate under diverse environmental and operational requirements. Minimizing unnecessary packet transmissions can conserve energy, which is a vital consideration given that IoT devices often are battery-dependent. In conclusion, the adaptive optimized ECHO protocol for LoRa Mesh Networks demonstrated a promising approach to overcoming the challenges in low-power, long-range wireless communication. Its focus on adaptability, efficiency, and sustainability aligns with the evolving needs of modern wireless networks, positioning it as a significant contribution to the field of wireless communication and IoT.

This work opens up new avenues for future research to explore sophisticated adaptation mechanisms that can consider a more comprehensive array of network parameters, such as node density, mobility patterns, and data packet priorities. This approach is expected to optimize network performance and efficiency, particularly in diverse and changing network conditions. We are working on minimizing LoRa's network congestion by monitoring the current network load, whereas the re-broadcast delay could be dynamically adjusted to alleviate congestion during peak traffic periods. Also, the rebroadcast delay could be adapted based on the packet size. Larger packets, which occupy the communication channel for longer periods, might benefit from a longer delay to reduce the chance of collision, while smaller packets could be re-broadcasted more quickly to maintain network fluidity.

Another avenue is to develop a real-time dynamic response mechanism to collision rates. If the collision rate increases beyond a certain threshold, we could increase the rebroadcast delay, thereby reducing the probability of further collisions. Furthermore, the variability in data rates, particularly in IoT environments where devices operate under different constraints, suggests the need for a rebroadcast delay that adapts to the current data rate. A higher data rate could allow for shorter delays, as packets are transmitted more quickly, whereas a lower data rate might necessitate longer delays.

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