Efficient Rebroadcast Location-Unaware Protocol for LoRaWAN Mesh Networks in the IoT Domain

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***Abstract*—Long-range Wide Area Network (LoRAWAN) is one of the most widely used low-power wide-area network technologies for enabling long-range and extensive coverage for Internet of Things (IoT) ecosystems. The network performance and sustainability metrics are crucial to effectively and efficiently implementing such IoT ecosystems. However, existing broadcasting protocols (e.g., ECHO) typically suffer from high collision rates and low network throughput when deployed in the IoT domain and, thus, may adversely impact the network performance. Therefore, a key objective in designing broadcast routing protocols in IoT is to increase the packet delivery success rate while reducing the packet collision rate. In this paper, we present an efficient rebroadcast location-unaware protocol for LoRaWAN mesh networks in the IoT domain. The proposed protocol dynamically adjusts the rebroadcast delay (i.e., timing) based on the network conditions. We in-depth analyzed the critical performance parameters (i.e., rebroadcast delay, packet size, and re-transmission strategy) that influence LoRaWAN mesh networks in various IoT environments operating in a low-data-rate context. As a result, we identified the causes of higher collision rates and, consequently, low network throughput in such a context. Experimental results showed that our protocol outperformed the ECHO protocol regarding the packet collision rate and energy efficiency.**

***Index Terms*—LoRa; LoRaWAN; IoT; Network Performance; Collision Rates; Network Throughput; ECHO.**

I. Introduction

Long Range (LoRa) has emerged as a powerful technology for long-range communication in low-power and low-capacity wireless networks through spread spectrum modulation [1], especially in the Internet of Things (IoT) domain [2]. The IoT ecosystem is an engineered system integrating computational algorithms with physical sensing components and processes. The computational algorithms coordinate and communicate with sensors monitoring cyber and physical indicators and actuators modifying the cyber and physical environment [3], [4]. IoT ecosystems can scale to billions of end devices (i.e., sensors and actuators) connected to gateways, which act as the aggregation points for a group of sensors and actuators to coordinate the connectivity of these devices to each other and an external network [5].

Long-range Wide Area Network (LoRAWAN) is a Low-Power Wide Area Network (LPWAN) technology [6] that offers wide-area coverage to low-power IoT devices. LoRAWAN is suitable for long-distance, low-power consumption, low-bandwidth, and multi-connection IoT devices. Existing broadcast protocols (e.g., ECHO [7]) suffer from high collision rates in dense mesh IoT networks, leading to diminished network performance and dropping the overall Packet Delivery Ratio (PDR) over time [4].

This paper presents an optimized broadcast routing protocol designed to enhance the performance efficiency of LoRAWAN mesh networks in the IoT domain by mitigating high collision rates. Specifically, we extended and ported the ECHO protocol, initially proposed for Mobile Ad Hoc Networks (MANETs). The ECHO protocol is a broadcast backbone for MANETs, in which network nodes transmit and listen to echo packets to determine their role in the network. When deployed in a MANET environment, ECHO was experimentally evaluated as a deterministic, source-independent, and fully distributed nature, balancing battery consumption across the nodes while proving effective in MANET environments with mobility. However, when deployed in the IoT domain, the ECHO protocol suffers from degraded network performance.

We conducted a set of real-world experiments using LoRa hardware to evaluate the effectiveness and efficiency of the proposed routing protocol using various network configurations. Most notably, we found that a significant decrease in the average Packet Collision Rate (PCR) from 20% to 14%, alongside an increase in Network Throughput (NT) from 80 to 90 packets per minute. In addition, our protocol achieved a packet success rate of over 89% compared to 85% for the ECHO protocol, despite a marginal rise in average network latency.

The proposed protocol also demonstrated enhanced energy efficiency, potentially increasing the battery lifespan of the IoT 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.

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 protocol, respectively. Section V experimentally evaluates the protocol in terms of 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 research on optimizing routing protocols in MANETs and LoRa networks underscores the importance of minimizing overhead and improving network efficiency [8]–[10]. The ECHO protocol [7], tailored for LoRa mesh networks, is engineered to facilitate efficient message delivery across network nodes. This protocol operates in two distinct phases: the Full Flood (FF) and the Pruned Flood (PF).

In the FF phase, a data packet is initiated to identify key nodes for a network-wide broadcast route, utilizing details such as the packet's origin, sender, previous sender, and a unique sequence number. Subsequently, an echo packet is transmitted to these key nodes to establish the optimal broadcast route, also known as the backbone.

Transitioning to the PF phase occurs once these key nodes are pinpointed. During this phase, only the identified nodes participate in relaying subsequent data packets, which markedly enhances network operational efficiency. The PF mode significantly curtails the volume of transmissions compared to the FF mode, thereby boosting the efficiency of network communication. The FF mode is reactivated only in response to substantial topology changes to ensure the broadcast route remains accurate and aligned with the current network configuration. The design of Echo aims to strike a balance between achieving comprehensive network reachability and reducing unnecessary transmissions, an essential strategy in LoRa environments where bandwidth and energy conservation are crucial [11], [12]. Additionally, this method aids in evenly distributing the load among various nodes, which promotes a longer network lifespan and stability.

In the ECHO protocol, nodes can exist in one of three states: Not Critical, Pending, and Critical. Initially, all nodes are in the Not Critical state. When a node in this state receives an FF packet, it broadcasts a modified version of the FF packet, updating the previous-sender field in the packet's header to its unique ID, and transitions to the Pending state. If a subsequent node receives this FF packet and identifies the previous-sender field, it acknowledges having received an echo message and shifts to the Critical state. This Critical status signifies that the node is integral to the network's broadcasting backbone and is tasked with forwarding further PF packets. Conversely, if an FF packet does not fulfill this criterion within a predetermined timeout period, the node reverts from the Pending to the Not Critical state.

B. LoRa Technology

LoRa technology represents a significant breakthrough in low-power wireless communication, especially within the Internet of Things (IoT) sector [13]. Designed for long-range communication while minimizing power usage, LoRa is well-suited for deployment in areas like smart city applications, agriculture, and environmental monitoring [4], [14], [15]. Key features of LoRa include its long operational range, high resistance to interference, and low data rate transmission. These features make it particularly beneficial for battery-operated IoT devices [16]. However, the inherently low data rates of LoRa introduce specific challenges in network protocol optimization, requiring modifications to traditional MANET protocols like the ECHO protocol to enhance efficiency in IoT contexts [3].

Significant progress has been made in refining LoRa communication strategies, as seen in the literature. One notable advancement is the use of an adaptive spreading factor, which optimizes network performance to meet the diverse demands of various applications while ensuring reliable and efficient data transmission [13]. Moreover, the adoption of private servers for managing LoRa communications and the associated data visualization are crucial aspects of IoT implementations. Such server architectures provide greater control and security for LoRa networks, which is vital for managing sensitive IoT data.

The integration of advanced data visualization tools is also critical for making sense of the vast amounts of data generated by IoT devices. This combined strategy of employing private servers and sophisticated data visualization tools plays a crucial role in enhancing IoT solutions, facilitating effective data management, detailed analytics, and strategic decision-making. These enhancements highlight the backend infrastructure's increasing complexity and its critical role in the IoT ecosystem. Together, these adaptive techniques reflect the ongoing evolution of low-power wide-area network technologies, marking a significant progression in the field [6], [17].

C. Existing Optimization Efforts in MANETs and LoRa Networks

At the heart of our routing optimization strategy is the deliberate implementation of extended delays before packet rebroadcasts within the ECHO protocol. This approach is supported by research from Gupta and Kumar [18], which validates the effectiveness of controlled transmission delays in increasing network throughput and reducing collisions within wireless networks. The authors emphasize the pivotal importance of managing packet collisions and refining transmission timings to enhance overall network performance.

In the specific realm of LoRa networks, a variety of methods have been investigated to improve data transmission efficiency while respecting the unique constraints associated with LoRa technology. Innovations such as adaptive data rate control [19], sophisticated power management techniques [20], and the optimization of packet dimensions and timing of transmissions

[21] illustrate the industry's commitment to optimizing performance. Our study extends these concepts by focusing on the optimization of rebroadcast protocols that are not dependent on the specific location information within IoT networks. By strategically increasing rebroadcast delays, our protocol aims to minimize the frequency of collisions and unnecessary transmissions. This not only preserves network bandwidth and reduces power consumption but also extends the operational lifespan of IoT devices, which are often constrained by battery life. This paper delves deeper into these techniques, showcasing their practical impacts and potential in modern wireless communication frameworks.

III. Design

The fundamental principle of our optimization strategy for the ECHO protocol in LoRa networks is based on the intentional extension of the delay before packet rebroadcasting. This tactic is particularly suited to the intrinsic characteristics of LoRa technology, which include low data rates and extended-range communication capabilities [5], [22]. In networks with low data rates, the window for potential packet collisions is inherently wider because each transmission takes longer to complete.

Our approach strategically increases the rebroadcast delay to stagger the transmission times across different nodes, thereby diminishing the likelihood of simultaneous transmissions that cause collisions. This method is inspired by the principles identified by Gupta and Kumar [18], who showed that deliberate control over transmission delays can significantly reduce collision rates and boost overall network throughput. Additionally, by prolonging the rebroadcast delay, nodes are afforded additional time to detect echo messages from their neighbors, which reduces unnecessary transmissions and enhances the efficient use of the network's constrained bandwidth.

The ramifications of increasing the rebroadcast delay within the ECHO protocol impact two critical areas of network performance: efficiency and collision rates. In terms of efficiency, this modification is anticipated to decrease the total number of transmissions needed to spread a packet throughout the network. This decrease results from fewer collision-induced retransmissions and more strategic use of transmission time [13]. With regard to reducing collision rates, our strategy utilizes the extended delay to lower the incidence of packet collisions. In wireless networks, particularly those with low data rates such as LoRaWAN, collisions can severely impair network performance and dependability. By implementing a protocol where nodes are less likely to transmit at the same time, we create a more synchronized and collision-resistant communication environment. This change not only enhances the likelihood of successful packet deliveries but also significantly contributes to the network's overall robustness and reliability, thereby supporting a more stable and efficient network operation in diverse deployment scenarios.

The design and implementation of our protocol are based on a comparative analysis that posits the benefits of extending the rebroadcast delay to decrease collision rates and improve network throughput. As illustrated in Algorithm 1, we modified the `ScheduleRebroadcast` function by incorporating an additional delay parameter. This adjustment prolongs the waiting period before rebroadcasting. Furthermore, we expanded the `HeardEcho` procedure to enhance the echo detection timeframe to accommodate this extended delay. Consequently, this adjustment ensures that nodes listen for an echo message over a longer duration, preventing them from rebroadcasting if the message has already been transmitted by another node.

Algorithm 1 A Pseudocode of the Proposed Rebroadcast Location-Unaware Protocol for LoRaWAN Mesh Networks in the IoT Domain

```
Global Variables:
    baseDelay                          ▷ Base delay in milliseconds
    maxDelay                           ▷ 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, maxDelay)
        currentDelay ← currentDelay × 1.5
procedure HEARDECHO(packet)
    Listen for packet rebroadcast by other nodes
    if heard then
        return True
    else
        return False
```

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 [7]. Also, the maxi-

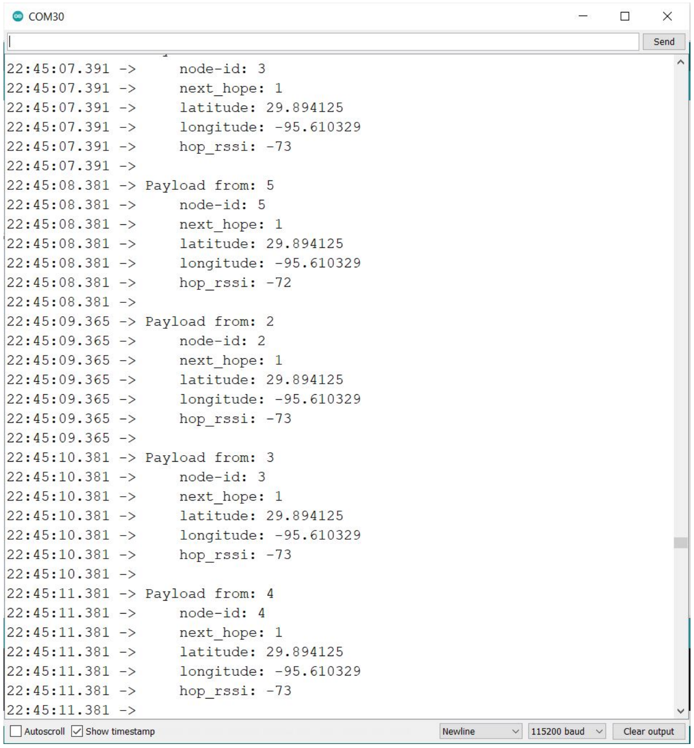

Fig. 1. Real time incoming payload in serial monitor.

mum rebroadcast delay is adjusted and recalculated from the original parameters to enhance network performance. This recalibration 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.

IV. Implementation

We have prototyped our routing protocol 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.

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 1. 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 IoT ecosystem.

Second, the LoRa ED (shown in Figure 2) is a versatile unit that boasts comparable components, including a LoRa HopeRF 95w transceiver, an ESP32 microcontroller mounted

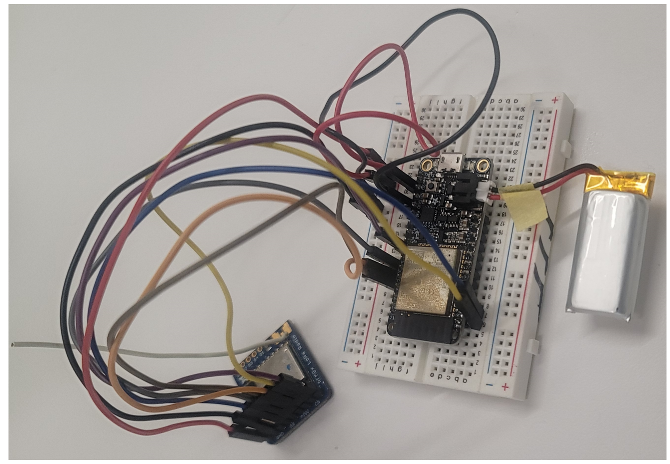

Fig. 2. The Hardware Design of a LoRa End Device.

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 IoT ecosystem.

Table I shows the experimental parameters of our real-world testbed, which was conducted in the Greater Houston Area. Five people –riding five vehicles– participated in a set of experiments to assess the performance of the proposed protocol. We initially used 4 LoRa EDs attached to mobile cars (see Figure 3) using a scotch tape driving at 4 miles per hour. We then gradually increased the number of EDs up to ten nodes during 60 minutes, covering a distance of 4 miles. 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.

TABLE I
Testbed Experimental Parameters

Parameter	**Value**
Number of ED Nodes	4-10
Area	2-4 miles
Speed of Nodes	0-4 miles/hr
Data Rate	5 Kbps
Packet Size	40 Bytes (payload and overhead)
Test Duration	2 Hrs

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.

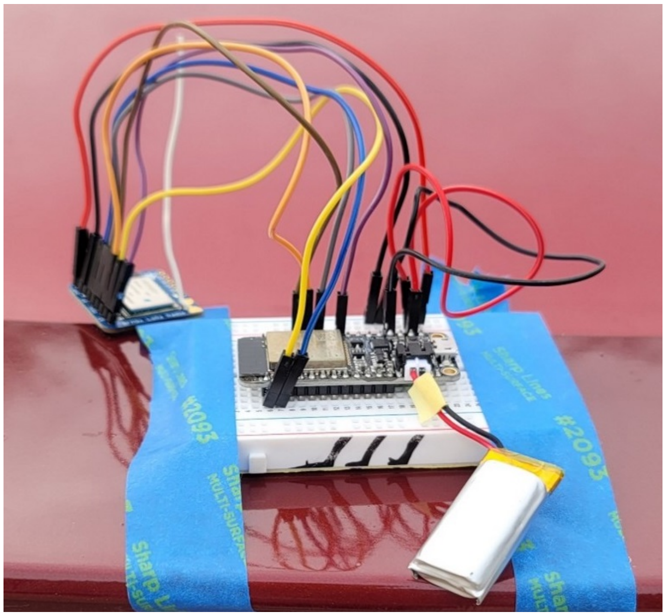

Fig. 3. A LoRa End Device Mounted on a Mobile Vehicle.

V. Evaluation

This section presents a theoretical analysis that shows the effectiveness of the optimized protocol in the IoT environment. Then, it demonstrates the experimental results of the real-world testbed presented in Section IV.

A. Theoretical Analysis

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 re-broadcast delay was set to 50ms, and the average collision rate was measured to be 20%. Therefore, the total collision time, $T_{\text{collision\_echo}}$, in ECHO can be calculated as follows [4]:

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

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:

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

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 $T_{\text{On\_Air}}$:

$$T_{\text{maxDelay}} = 400 - 76.8 = 323.2\text{ms} \quad (4)$$

B. Experimental Results

In this study, real-world LoRa hardware setups were used to evaluate the performance of our optimized protocol. The findings indicate a significant enhancement in performance over traditional protocols such as ECHO, particularly in terms of Multi-Point Relay (MPR), flooding, and Opportunistic Announcement (OA).

As depicted in Table 1, using ten LoRa End Devices (EDs), the experimental results from our testbed demonstrated that our protocol achieved a 40% reduction in battery consumption compared to ECHO, while also reducing packet transmission by threefold. Additionally, packet delivery success increased from 85% to 89%, though this was accompanied by a minor rise in average network latency..

TABLE II
Experimental Results

Metric	ECHO	Optimized Protocol
Collision Rate	20%	14%
Throughput (pkt/min)	40	46
Packet Delivery Rate	85%	89%
Battery Lifespan (hr)	48	52

Relative to ECHO, our enhanced protocol demonstrated a 10% decrease in collision rate, a 10% per minute improvement in overall throughput, a 4% enhancement in Packet Delivery Ratio (PDR), and a four-hour extension in battery life. This increase in throughput was achieved without exceeding the "on the air" limitations associated with LoRa networks, ensuring compliance with regulatory standards and maintaining operational effectiveness.

These advancements highlight the critical role of eliminating explicit control packets during the Forwarding Phase (FF), which effectively reduced the overall communication complexity. Furthermore, our protocol is designed to be independent of specific Medium Access Control (MAC) or Radio Frequency (RF) characteristics and is unaffected by traffic variability. Thus, it is scalable and supports the sustainability of multi-hop LoRa mesh networks.

Figure 4 illustrates the performance comparison between ECHO and our enhanced protocol, specifically focusing on the average PDR improvement. The chart reveals a consistent PDR increase of at least 4% as the number of LoRa EDs is raised from 4 to 10, maintaining all other variables constant, along with a notable reduction in overall communication burden.

Figure 5 illustrates the Average Collision Rate (ACR) of our protocol compared to ECHO. As shown in the figure, we measured a notable decrease in ACR from 20% to 14%. This indicates that the optimized protocol can significantly mitigate higher collision rates in ECHO under the IoT settings.

VI. Discussion and Conclusions

This paper introduces an optimized routing broadcast protocol tailored for LoRaWAN Mesh networks within IoT systems. Our proposed protocol dynamically modifies the rebroadcast delay in ECHO based on fluctuating network conditions,

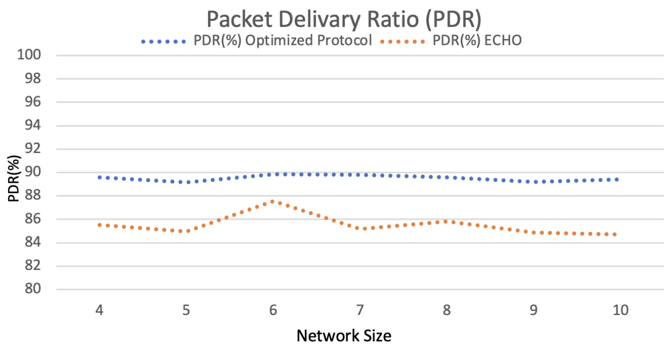

Fig. 4. The Average PDR of the Optimized Routing Protocol Compared to ECHO.

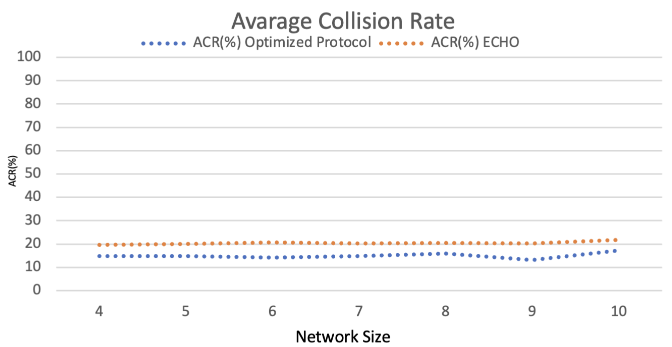

Fig. 5. The Average Collision Rate (ACR) of the Optimized Routing Protocol Compared to ECHO.

tackling critical issues prevalent in IoT networks. Central to our adaptive delay mechanism is the intelligent adjustment of the rebroadcast delay up to a maximum of 400 milliseconds, which effectively manages the packet "on the air" time and reduces potential packet collisions during rebroadcast. This adjustment significantly lowers network congestion, thus improving the network's overall throughput and reliability—an essential enhancement for LoRa mesh networks in the IoT sphere, where effective communication must be maintained despite bandwidth limitations and energy constraints.

The implementation and evaluation of this protocol in a real-world testbed across various deployment scenarios have yielded deeper insights into its operational performance and highlighted potential areas for further enhancements.

Moreover, the protocol's capability to readjust to changing network conditions marks a significant advancement in the design of intelligent IoT systems. This adaptability is crucial as IoT devices frequently operate in diverse environmental and operational settings. By minimizing unnecessary packet transmissions, the protocol helps conserve energy, which is particularly important given the battery dependency of many IoT devices.

In summary, the Adaptive Optimized ECHO Protocol for LoRa Mesh Networks presents a robust solution to the challenges of low-power, long-range wireless communication. Its focus on adaptability, efficiency, and sustainability meets the demands of modern wireless networks, making it a valuable contribution to the fields of wireless communication and IoT.

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