An Empirical Analysis of LoRa Mesh Configurations for Enhancing Network Efficiency Under Constrained Dwell Time Environments

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***Abstract*—Long-range Wide Area Networks (LoRaWAN) have recently gained popularity by offering wide-area coverage to low-power Internet of Things (IoT) monitoring devices in remote areas. LoRAWAN suits long-distance, low-power consumption, low-bandwidth, and multi-connection IoT devices. However, efficient communication in IoT networks is crucial, particularly in dense environments where regulatory constraints like dwell time limits pose significant challenges. This paper conducts an empirical and experimental analysis of LoRa mesh-based networks to explore the optimal configuration settings to enhance its performance while adhering to constrained dwell time restrictions. We conducted a set of real-world experiments using LoRa hardware to evaluate the effectiveness and efficiency of LoRaWAN communications under various configurations, including payload size, Spreading Factor (SF), and bandwidth. The experimental results showed that altering these parameters could violate dwell time regulations. For instance, setting the SF to SF7/125kHz or SF8/125kHz leads to exceeding the dwell time in congested environments. Also, our experiments indicated that using 500kHz bandwidth provides the network's best performance under constrained dwell time environments. Furthermore, our analysis highlighted the critical role of Full Flood (FF) intervals and rebroadcast delays of broadcast protocols (e.g., ECHO) in managing overall airtime and reducing network congestion. We demonstrated how strategic adjustments to these configuations can maintain compliance and optimize performance by calculating the maximum rebroadcast delays for each configuration.**

***Index Terms*—Empirical Analysis,LoRa, LoRaWAN, Network Efficiency, Optimal Configuration, Dwell Time.**

I. Introduction

Long-Range (LoRa) technology has became a dominant medium for long-range communication in low-power and low-capacity wireless Internet of Things (IoT) networks, making it ideal for applications in smart cities, agriculture, and environmental monitoring [1]–[4]. LoRaWAN, an open system based on robust LoRa modulation, is highly suitable for rural coverage using low-power IoT devices [5].

In LoRaWAN networks, the dwell time refers to the maximum time allowed for transmission to occupy a channel, regulated by regional standards to ensure fair spectrum use and prevent interference [6]. Constrained dwell time, therefore, refers to these strict limits on how long a device can transmit continuously on a given channel. These constraints pose a significant challenge in dense environments, as exceeding the dwell time can lead to regulatory non-compliance and degrade network performance. Efficient airtime management within these constraints is crucial, especially in IoT networks where multiple devices may attempt to transmit simultaneously. This paper provides insights into optimizing LoRaWAN configurations to maximize network efficiency while adhering to these dwell time limitations.

In the context of the LoRa mesh network, where LoRa nodes are connected to each other and not necessarily connected to a LoRa hub, the network configuration and optimal parameter selection can significantly impact its performance and stability. For instance, in dense LoRaWAN environments, airtime and FF interval management plays a pivotal role in the network performance under constrained dwell time environments [7].

The FF interval, also called rebroadcast delay, is a crucial component in flooding-based zero-control routing protocols (e.g., ECHO [8]) that determines the frequency of network-wide data updates through message flooding. In other words, FF intervals are the durations between consecutive rebroadcasts in a full network-wide flood. FF intervals significantly influence overall airtime consumption, as shorter intervals lead to more frequent rebroadcasts of messages across the network, thereby increasing airtime usage.

Regular and scheduled rebroadcasting is important in dense LoRaWAN environments as it helps reduce transmission overlap, minimize potential collisions, and manage network congestion effectively [5]. The efficient management of these intervals is essential for maintaining efficient network op-

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erations and ensuring reliable communication, especially in the IoT domain. This empirical study explores the optimal configuration of LoRaWAN mesh networks based on specific payload requirements, focusing on pre-set configurations that maintain compliance with dwell time limits while maximizing network efficiency. In this paper, we tried to address the gap in the literature by providing empirical insights into LoRaWAN performance under constrained dwell time regulations in dense environments. Unlike existing work [9]–[12], this study examines the combined effects of parameters like Full Flood intervals, rebroadcast delays, and payload sizes on congestion and airtime, offering novel guidelines for optimizing real-world deployments.

This paper provides definitive guidelines for network administrators on configuring the optimal FF interval through a systematic analysis of various transmission configuration parameters, including Spreading Factor (SF), bandwidth, coding rate, and payload size. We deployed a network of LoRa Edge Devices (ED), each equipped with ESP32 microcontrollers, HopeRF 95w transceivers, Neo-6m GPS modules, and batteries, across a 10-mile radius in the Greater Houston Area. Our experiments varied payload sizes from 25 to 242 bytes and tested different values of SF and bandwidth. Theoretical analysis shows that the optimal configurations, such as SF9/125kHz, balance range, airtime, and congestion, stay within regulatory limits. Conversely, configurations like SF10/500kHz fail due to excessive airtime from higher payload segmentation, reinforcing the importance of strategic parameter selection.

The rest of the paper is organized as follows: Section II presents the background and related work. Section III presents the experimental setup of this empirical analysis. Section IV discusses the obtained experimental results. Finally, Section V encapsulates the conclusions drawn from this research and suggests potential directions for future work.

II. Background and Related Work

A. ECHO Protocol

Efficient communication in LoRaWAN mesh networks is paramount in Mobile Ad-hoc Networks (MANETs) and IoT. The ECHO protocol, designed explicitly for LoRaWAN mesh networks, emphasizes reducing overhead and enhancing network efficiency [13]. ECHO operates in two phases: the Full Flood (FF) and the Pruned Flood (PF). The FF phase initiates a network-wide broadcast to determine critical nodes based on various metrics, including the packet's origin and sequence number. An ECHO packet is sent to these critical nodes to establish an optimized broadcast route or backbone [8].

Transitioning to the PF phase allows the network to operate more efficiently by limiting data transmissions to only the identified critical nodes. This method significantly reduces the transmission volume compared to FF mode, thereby enhancing communication efficiency and conserving network resources. FF mode is reactivated in response to substantial topology changes to update the broadcast route, ensuring adaptability and reflection on the current network configuration. The dual-phase operation of ECHO is designed to balance comprehensive network coverage with minimal redundant transmissions, which is crucial for conserving bandwidth and energy [13].

LoRa ED runs on ECHO protocol [8], has three states: not critical, pending, and critical. Nodes are initially marked as not critical transitions and pending upon receiving an FF packet, which they then rebroadcast with updated headers. If an ECHO message is returned, the node shifts to a critical state, indicating its role in the robust broadcasting backbone. Nodes revert to not critical if conditions for transition are not met within a set timeout, optimizing network responsiveness.

B. LoRaWAN Configuration

In a previous work [14], we extended the ECHO protocol by dynamically adaptation the SF depending on the network condition to overcome the inherent limitations of low data rates in LoRa networks for effective performance while managing energy consumption efficiently.

In LoRaWAN mesh networks utilizing the ECHO protocol, the configuration setting for FF intervals plays a crucial role in effectively managing the network's airtime and overall performance. These intervals significantly influence the frequency at which nodes transmit data, impacting airtime consumption and the potential for network congestion. Optimally adjusting these intervals is critical to minimize data collisions and maximize the efficiency of the network's bandwidth [15].

FF intervals, when properly optimized, can substantially reduce unnecessary network traffic, thereby enhancing the longevity and stability of the system. Furthermore, selecting the appropriate values for these intervals based on the payload size and network conditions is crucial for balancing network reachability and resource conservation. Such strategic parameter settings ensure that the network operates within the constraints of regulated dwell times, optimizing performance without sacrificing compliance or efficiency.

Moreover, the importance of FF intervals or rebroadcast delays extends to how they contribute to overall airtime management. By controlling the rate of message rebroadcast in the network, these intervals directly affect how long the network is actively transmitting, which in turn impacts energy consumption and channel availability. The optimal configuration of these intervals, along with other critical parameters such as SF, Bandwidth (BW), and payload size, is essential.

The SF affects the signal's range and penetration. Higher SF increases the range of coverage and airtime, which can lead to more significant airtime consumption. On the other hand, the bandwidth influences the data rate, in which higher bandwidth allows for faster data transmission, reducing airtime per transmission and potentially increasing susceptibility to interference. The Payload Size dictates the amount of data transmitted in each message. Larger payloads increase the necessary airtime per transmission but reduce the need for frequent transmissions.

Optimizing these parameters (i.e., SF and BW) based on payload sizes and network demands ensures efficient data transmission, minimizes airtime, and conserves network resources. Also, it allows for tailored configurations that meet specific application needs without overburdening the network infrastructure. This paper will explore these dynamics in depth, focusing on scalable and energy-efficient monitoring solutions tailored for regions with limited cellular coverage. It will highlight the critical role of FF interval optimization alongside SF, BW, and payload adjustments in achieving efficient, reliable, and regulatory-compliant network operations.

C. Existing Efforts for Optimizing LoRaWAN Configuration

Several works in the literature have addressed the optimization of a network configuration for achieving better performance and using LoRaWAN features amidst increasing device deployments [9]–[12].

G. Premsankar et al. [10] present an approach to optimize LoRa network configurations in smart cities. The authors utilized integer linear programming to enhance scalability and reliability while managing energy consumption and network performance. This study addresses the challenges posed by increased device deployments, highlighting the importance of optimal SF selection and power control to mitigate contention and interference in unlicensed radio bands.

Another study [12] explored the throughput optimization challenge in multi-gateway LoRaWAN networks. The proposed research approach employed queueing analysis and joint packet decoding techniques to improve resource management and maximize network throughput. This study emphasized the need for efficient resource allocation and interference mitigation strategies to handle the increased network load.

Paul et al. [9] proposed an approach focusing on planning and configuring LoRaWAN networks, which involved optimizing transmission configurations and routing to enhance network performance and energy efficiency. The authors proposed strategies for effectively deploying and managing LoRaWAN in various environments, considering cost, energy consumption, and transmission reliability. Similar to our work, an empirical analysis was conducted on LoRaWAN mesh networks to evaluate the impact of different configuration settings on network efficiency under constrained dwell time environments. This study revealed that configurations such as SF7/125kHz and SF8/125kHz can exceed dwell time regulations in congested settings, whereas a 500kHz bandwidth generally performs better. This analysis underscores the necessity of strategic adjustments to network configurations to maintain compliance and optimize performance.

Ahmed et al. [11] presented an approach for improving the geolocation performance of LoRaWAN by utilizing adaptive spreading factor techniques. The authors demonstrated that dynamically adjusting the SF based on environmental conditions can significantly enhance location accuracy, which is critical for applications requiring precise geolocation data. Another study [15] explored the deployment of private LoRaWAN servers to provide network coverage in rural communities. The authors integrated the Grafana data visualization tool to enhance the system's monitoring and management capabilities.

In summary, the existing work focusing on optimizing LoRaWAN configurations [9], [10], [12] still needs to provide more practical solutions to improve scalability, throughput, and energy efficiency in real-world smart city applications. In addition to conducting an empirical analysis on optimizing the network configuration, our work addresses the challenges of increasing device density and regulatory constraints, ensuring reliable and efficient communications.

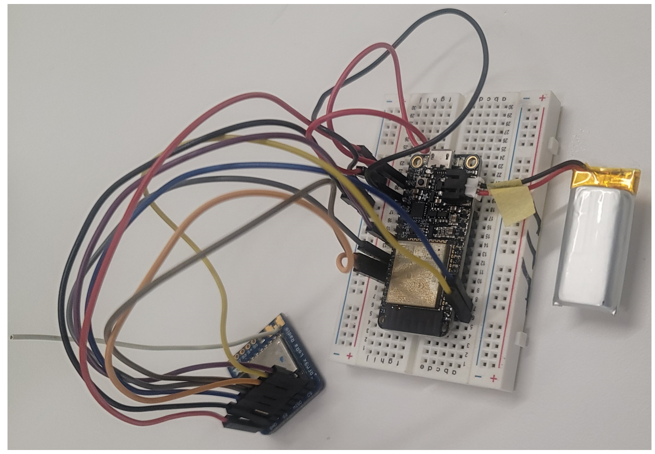

Fig. 1. The Hardware Design of a LoRa End Device.

III. Experimental Setup

Our experimental setup involved deploying ten LoRa EDs (shown in Figure 1), each outfitted with a LoRa ESP32 Arduino microcontroller, HopeRF 95w transceiver, Neo-6m GPS module, and batteries. Each node can communicate over an average range of approximately 2 miles, with mobility up to 4 miles per hour. We strategically positioned these nodes to establish a network that effectively covered a radius of up to 10 miles during the 60-minute duration of our experiment, conducted in the Greater Houston Area.

This real-world testbed was used instead of a simulation environment to provide more accurate and practical insights into the performance of the LoRa mesh network under natural environmental conditions. The choice of 10 nodes was made to balance the complexity and manageability of the experiment while providing meaningful insights into the performance of a LoRa mesh network of this scale. This scale represents small to medium-sized deployments, such as smart city applications, environmental monitoring, or agricultural setups, where a moderate number of devices can provide comprehensive coverage and reliable data collection.

Table I shows the experimental parameters of our real-world testbed. The data rate and packet size were set to 5 Kbps and 40 Bytes, respectively. The payload sizes in our experiments varied gradually from 25 to 242 bytes. The configuration readings were recorded during each experiment. LoRa technology allows choices of 125 kHz, 250 kHz, and 500 kHz for the bandwidth settings. In our experiments, we opted for 125 kHz and 500 kHz bandwidths to evaluate sensitivity, extended coverage range, energy efficiency, and the effectiveness of adaptive data rates within the U.S. regulations.

TABLE I
TESTBED EXPERIMENTAL PARAMETERS

Parameter	Value
Number of ED Nodes	10
Average Area Coverage	2 miles
Speed of ED Nodes	up to 4 miles/hr
Bandwidth	125kHz,500kHz
Packet Size	40 Bytes (payload and overhead)
SF	7-10 for 125 kHz and 7-12 for 500 kHz
Experiment Time	60 minute per configuration

In LoRa technology, SF is pivotal in adjusting the data rate, directly influencing the transmission range and power consumption. Higher SFs enhance range and interference robustness but at the cost of a reduced data rate and increased airtime, leading to greater power consumption. Conversely, lower SFs, such as SF7, provide higher data rates but offer reduced range and sensitivity. Our system's default setting was SF7, which was selected to balance throughput with range and energy efficiency. This setting is particularly advantageous in scenarios where monitoring nodes are relatively close to each other or the gateway, and where minimizing transmission time to conserve battery life is crucial.

A. Theoretical Analysis

According to the LoRa modulation configuration, the maximum bitrate, R, is set to 5,470 bits/sec, which is calculated as:

$$R = \frac{\text{BW}}{2^{\text{SF}}} \times \frac{SF}{CR} \tag{1}$$

where SF is the Spreading Factor, BW is the Bandwidth, and CR is the Coding Rate.

For the SF7/125kHz mode, SF, BW, and CR are set to 7, 125 kHz, and 4/5, respectively. First, the Symbol Rate is set to 976.5625 symbols per second, which is calculated as:

$$\text{Symbol Rate} = \frac{\text{BW}}{2^{\text{SF}}} = \frac{125,000}{2^7} \tag{2}$$

Second, the Bitrate, R, is set to 5,470 bps, which is calculated as:

$$R = \text{Symbol Rate} \times \frac{SF}{2^{\text{CR}}} \times \frac{4}{4+\text{CR}} \tag{3}$$

We assume that CR is equal to 1 for coding rate 4/5, then R is calculated as:

$$R = 976.5625 \times \frac{7}{1.3195} \times \frac{4}{4.8} \tag{4}$$

Equation (1) serves as a generalized formula for calculating the maximum bitrate, providing an overview of how core parameters –bandwidth (BW), spreading factor (SF), and coding rate (CR)– affect data transmission. In contrast, equation (3) applies this general formula to specific conditions in the study, using precise values (e.g., SF = 7, BW = 125kHz) and incorporating additional constants like the coding rate adjustment factor and symbols per second. Equation (1) establishes a foundational understanding, while equation (3) demonstrates the practical calculation for the experimental setup. This approach ensures transparency and consistency, making the theoretical and practical aspects of the bitrate calculation accessible for replication and analysis.

These calculations align with the given value of 5470 bits/sec for the SF7/125kHz mode. The key factors are the spreading factor, bandwidth, and coding rate, which together determine the effective bitrate for a given LoRaWAN configuration.

For calculating the Airtime (ms) with 20% congestion in mode SF7/125kHz, we set the maximum Bitrate and Payload Size to 5,470 bits/sec and 242 bytes, respectively. As shown in [14], the 20% collision rate represents a moderate level of network congestion when using the ECHO protocol with a FF retransmission delay of 50 ms. For simplicity, we assume a linear relationship between the collision and re-transmission rates. We calculated the Transmission Time, $\text{T}_{\text{transmission}}$, as:

$$T_{\text{transmission}} = \frac{\text{Packet Size (in bits)}}{\text{Data Rate (bps)}} = \frac{242 \times 8}{5470} \approx 353.93\,\text{ms} \tag{5}$$

The average Collision Time, $\text{T}_{\text{collision}}$, is calculated as:

$$T_{\text{collision}} = T_{\text{transmission}} \times \text{Collision Rate} \tag{6}$$

$$T_{\text{collision}} = 353.93 \times 0.20 = 70.79\,\text{ms} \tag{7}$$

Finally, the Total Airtime with Congestion, $\text{T}_{\text{On\_Air}}$, is calculated as,

$$T_{\text{On\_Air}} = T_{\text{transmission}} + T_{\text{collision}} \tag{8}$$

$$T_{\text{On\_Air}} = 353.93 + 70.79 = 424.72\,\text{ms} \tag{9}$$

IV. EXPERIMENTAL RESULTS AND ANALYSIS

This section presents the results obtained from our experiments, focusing on the airtime performance under different LoRaWAN configurations. We evaluate each configuration to determine compliance with dwell time limits and calculate the maximum rebroadcast delays.

A. Performance Analysis Without Congestion

Table II provides an in-depth analysis of the performance of various studied LoRaWAN configurations, highlighting the calculated airtime and experimental results in a congestion-free environment. Figure 2 compares the theoretical airtime with experimental results under ideal conditions without collisions.

The findings show that:

- **SF7/125kHz Configuration**: The calculated airtime is 353.93 ms, while the experimental result is 355.25 ms. The small difference demonstrates the accuracy of our calculations in a collision-free environment.
- **SF8/125kHz Configuration**: The experimental airtime is 320.46 ms, which is consistent with the theoretical value of 320.00 ms.
- **SF9/125kHz and SF10/125kHz Configurations**: Both configurations show that the experimental airtime closely aligns with the theoretical calculations, demonstrating robustness in congestion-free conditions.

The results indicate minimal deviation between theoretical and experimental airtime values, underscoring the reliability of our calculations for network design in ideal settings.

TABLE II
A PERFORMANCE COMPARISON OF THE THEORETICAL AND EXPERIMENTAL AIRTIME UNDER DIFFERENT MODES, BITRATES, AND PAYLOAD SIZES

Mode	Bitrate (bits/sec)	Payload Size (bytes)	Theoretical Airtime (ms)	Theoretical Airtime with 20% Congestion (ms)	Exp. Result: Airtime without Collision (ms)	Exp. Result: Airtime with 20% Collision (ms)
SF7/125kHz	5470	242	353.93	424.72	355.25	429.65
SF8/125kHz	3125	125	320.00	384.00	320.46	391.49
SF9/125kHz	1760	53	240.91	289.09	242.02	294.48
SF10/125kHz	980	11	89.80	107.76	92.45	118.37
SF7/500kHz	21900	222	81.10	97.32	85.26	105.14
SF8/500kHz	12500	222	142.08	170.50	145.11	178.93
SF9/500kHz	7000	222	253.71	304.46	257.89	314.79
SF10/500kHz	3900	222	455.38	546.46	456.25	549.65
SF11/500kHz	1760	109	495.45	594.55	496.56	600.41
SF12/500kHz	980	33	269.39	323.27	272.34	324.08

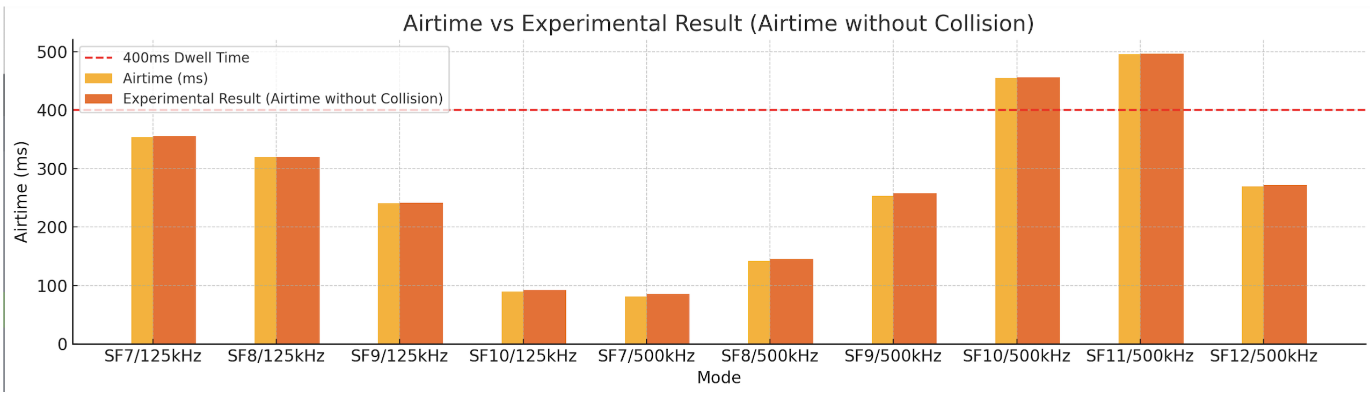

Fig. 2. Theoretical vs. Experimental Analysis of the Airtime without Collision (congestion-free network)

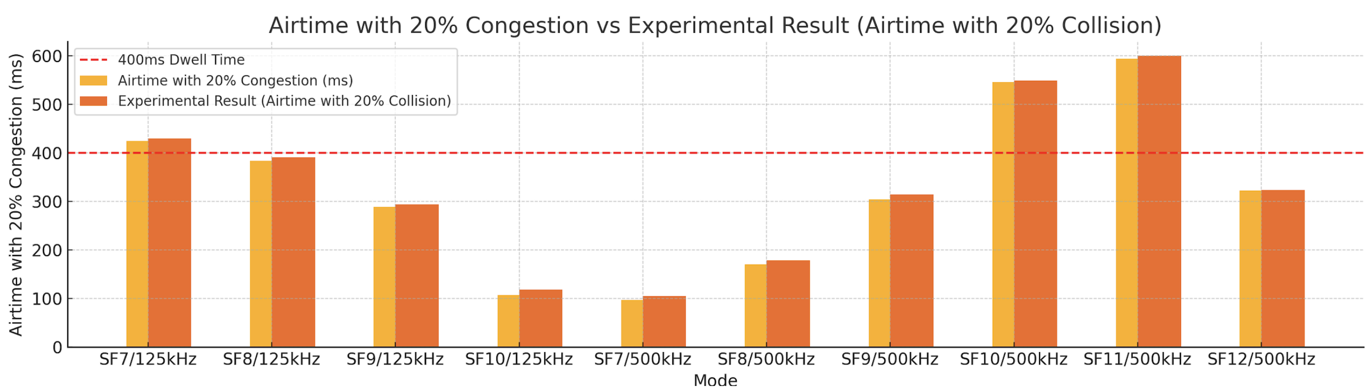

Fig. 3. Theoretical vs. Experimental Analysis of the Airtime with 20% Collision (dense network)

B. Performance Analysis Under Congested Conditions

Figure 3 and Table II show the calculated airtime and experimental results under congested conditions (20% collision rate). The performance of different configurations is analyzed to evaluate their suitability for broadcasting under constrained dwell time limits.

Key observations include:

- **SF7/125kHz Configuration**: The calculated airtime with congestion is 424.72 ms, while the experimental result is 429.65 ms, exceeding the 400 ms dwell time limit. This indicates that SF7/125kHz is unsuitable for congested environments due to excessive airtime.
- **SF8/125kHz Configuration**: The experimental airtime with 20% collision is 391.49 ms, which is within the dwell time limit, making this configuration suitable for broadcasting under moderate congestion.
- **SF9/125kHz and SF10/125kHz Configurations**: Both configurations remain well within the dwell time limits even under congestion, demonstrating their robustness for dense network environments.

C. Effect of Bandwidth on Airtime Performance

The experiments also evaluated the impact of different bandwidth settings (125 kHz and 500 kHz) on airtime performance:

- **500kHz Bandwidth Configurations**: Configurations using 500kHz bandwidth generally showed lower airtime compared to 125kHz configurations, making them more suitable for environments with higher data transmission needs.
- **SF10/500kHz and SF11/500kHz Configurations**: Both configurations exceeded the 400 ms dwell time limit under congested conditions, deeming them unsuitable for broadcasting at the given bitrate and maximum payload.

D. Discussion

The results underscore the importance of carefully selecting and optimizing LoRaWAN parameters based on specific network conditions. Configurations such as SF7/125kHz and SF8/125kHz are sensitive to increased traffic and may exceed dwell time limits under congestion, while SF9/125kHz and SF10/125kHz configurations offer more robust performance.

Bandwidth selection also plays a critical role, with 500kHz bandwidth providing better airtime performance in most scenarios. However, higher spreading factors (e.g., SF11/500kHz) can lead to significant increases in airtime under congestion, emphasizing the need for strategic adjustments to network parameters. In conclusion, this analysis provides valuable insights for network administrators on optimizing LoRaWAN configurations to ensure regulatory compliance and efficient network performance in both ideal and congested environments.

V. Conclusion

This paper focused on identifying optimal configuration values for LoRaWAN networks to ensure efficient network performance within constrained dwell time environments. Through a comprehensive analysis of various transmission parameters, including SF, bandwidth, and payload size, we explored their impacts on airtime and network congestion, specifically in dense network environments where efficient airtime management is critical. Our experimental setup involved deploying several LoRa EDs on mobile vehicles driving in the Greater Houston Area. These nodes, strategically positioned to cover a radius of up to 10 miles, were tested with payload sizes ranging from 25 to 242 bytes.

The experimental results showed valuable insights into the airtime performance under different configurations. We found that the SF7/125kHz and SF8/125kHz configurations exhibited airtime within acceptable limits under normal conditions but exceeded the dwell time limit under 20% congestion, indicating their sensitivity to increased traffic. The SF9/125kHz and SF10/125kHz configurations remained well within the dwell time limits even under congestion, demonstrating their robustness. Configurations using 500kHz bandwidth generally showed lower airtime, making them more suitable for environments with higher data transmission needs. However, SF10/500kHz and SF11/500kHz configurations violated the dwell time constraints, deeming them unsuitable for broadcasting with the given bitrate and maximum payload under congested conditions.

In conclusion, this empirical study underscores the importance of carefully selecting and optimizing LoRaWAN parameters based on specific payload requirements and network conditions. These findings aim to assist network administrators and designers in making informed decisions that balance operational efficiency and regulatory compliance, ultimately contributing to more reliable and scalable IoT deployments.These findings can be directly applied to real-world scenarios such as smart agriculture, environmental monitoring, and urban IoT deployments, where optimizing network performance under constrained dwell time regulations is critical. Future work will explore adaptive configurations and real-time adjustment mechanisms, including dynamic spreading factor and bandwidth selection, to improve performance in diverse environmental and traffic conditions.

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