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Traffic control strategies for LPWAN in multigateway environments

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Abstract—This work focuses on managing upstream traffic in multigateway Low-Power Wide Area Networks (LPWANs) to support efficient traffic from thousands of nodes. As LPWANs face challenges such as increased collision probability and network saturation due to node densification, our research introduces a distributed and probabilistic traffic control protocol. This protocol aims to effectively manage network traffic, reduce collisions, and mitigate saturation issues, ensuring better performance and scalability in densely populated IoT environments. The protocol enables nodes to dynamically adapt their traffic to meet application needs, such as transmitting a defined number of measurements (K) within a designated time frame. This adjustment remains unaffected by the node count and network topology, focusing instead on the feedback message’s destination to the network nodes, which is crucial for dynamically adapting traffic intensity and reducing collisions. We explore two feedback transmission strategies: a synchronous one, where all gateways transmit feedback simultaneously to all nodes, and a round-robin one, where one gateway at a time sends feedback to nodes within its coverage area. Based on simulation results, our evaluated strategies achieve substantial performance improvements over the Baseline LoRaWAN. Specifically, they demonstrate a network lifetime increase of up to 93.12%, a success rate increase of up to 96.34%, and a packet delivery ratio increase of up to 14.97%. These findings highlight significant enhancements in both efficiency and reliability compared to traditional LoRaWAN configurations.

Index Terms—LPWAN, traffic control, probabilistic transmission, multigateway environments, AIMD, distributed approach, LoRaWAN, LoRaSim.

I. INTRODUCTION

LPWANs, referred to as Low Power Wide Area Networks, support applications like smart agriculture, metering, asset tracking, and environmental monitoring. Nevertheless, adapting to the evolving demands of these applications poses a significant challenge. As more devices join these networks, competition for limited bandwidth intensifies, potentially causing congestion and hindering scalability. This challenge is worsened by the substantial amount of data generated and the use of Aloha-based access protocols [1]–[3]. This is particularly significant for specific applications, such as environmental monitoring, where a particular amount of data must be transmitted within a predetermined time period. Excessive data transmission in a network can lead to congestion, increased collisions, and degraded performance. This can cause delays and packet loss, impacting the network’s efficiency and reliability. Conversely, insufficient data transmission hinders

the effectiveness of applications requiring timely data updates, such as environmental monitoring or industrial systems. Therefore, controlling the traffic is essential to maintain network reliability and efficiency, ensuring that applications receive the required amount of data within specified time intervals without causing unnecessary strain or inefficiencies in the network.

Addressing this challenge requires efficient traffic management solutions, particularly in multigateway environments. Existing solutions primarily prioritize reducing collisions and alleviating congestion rather than controlling traffic intensity [4]–[6]. In our prior research [7], we introduced the Distributed and Probabilistic Traffic Control approach (DiPTC). In DiPTC, we regulate traffic intensity by incorporating a feedback mechanism through binary control messages sent by the gateway. These messages enable nodes to dynamically adapt their traffic intensity, aligning with the diverse requirements of applications within a specific area, regardless of network topology. While single-gateway setups may suffice for smaller deployments or initial testing phases, transitioning to multigateway environments becomes essential for scaling IoT networks across larger geographic areas and meeting the increased demands for reliability, coverage, and data throughput [8], [9]. Adapting solutions to these environments requires addressing complexities such as managing overlapping coverage areas, optimizing load balancing across gateways, and ensuring synchronized data transmission. In this paper, we aim to adapt our approach to multigateway environments to enhance its applicability and realism. Specifically, we investigate two feedback transmission strategies: a synchronous approach where all nodes receive feedback simultaneously, and a round-robin approach where feedback is selectively delivered to nodes within each gateway’s coverage area. These strategies are designed to enhance the overall network performance in dynamic and scalable deployments.

The subsequent sections of this paper are structured as follows: Section II examines the necessity of a traffic control approach for LPWANs, while Section III details our proposed solution. Section IV outlines the simulation setup and scenarios used for validation, with results discussed in Sections V. Finally, Section VI concludes the paper, highlighting future research directions.

II. RELATED WORK

Traffic control is primordial for optimizing networks by reducing collisions, conserving energy, and alleviating con-

gestion, especially in LPWAN environments. Previous studies have examined different strategies: Mores *et al.* [5] devised a heuristic for adjusting LoRaWAN parameters based on signal strength and distance, and Quin *et al.* [6] introduced an algorithm to ensure fair channel access among IoT devices. Another approach includes traffic scheduling, where Kaburaki *et al.* [10] proposed a Q-learning method that autonomously adjusts transmission times to lower collision probabilities. However, these methods primarily prioritize collision mitigation rather than achieving overall traffic reduction.

Traffic control protocols commonly used in Internet networks, such as TCP and QUIC [11], [12], provide valuable insights for LPWANs. These algorithms, like the Additive-Increase/Multiplicative-Decrease (AIMD) algorithm, dynamically adjust sending rates and manage congestion. Based on these principles, we previously introduced a novel traffic control approach for LPWANs known as Distributed and Probabilistic Traffic Control (DiPTC), designed to meet specific application requirements within defined time periods [7]. DiPTC, drawing inspiration from AIMD principles, uses a reduction factor x_D to decrease traffic when the number of received messages is high and an increase factor x_I to boost traffic when the number of received messages is low. This approach ensures nodes adjust their transmission rates based on feedback from the network server through the gateway in each time period ΔT . To manage the constrained downlink message payload, feedback messages are simplified to binary values: 0 indicating excessive messages received and 1 indicating insufficient messages sent. Once traffic goals are achieved, no further downlink messages are transmitted, and nodes maintain their current transmission rate until the next time period. Node traffic intensity increases linearly with the coefficient x_I unless the network server receives more than the required K messages per ΔT , prompting nodes to decrease their traffic exponentially using the coefficient x_D . Traditionally, LoRaWAN downlink messages are unicast, individually sent to nodes primarily for acknowledgment or control information purposes [13]. However, DiPTC redefines downlink communication, turning it into a feedback mechanism where feedback messages are broadcast simultaneously to all nodes in the network. This innovation of broadcasting feedback messages transforms downlink communication from a series of individual interactions into a unified mechanism for real-time network monitoring and adaptive control. This shift provides significant advantages over traditional LoRaWAN by enabling broader network insight, more responsive management, and enhanced scalability and efficiency in LPWAN environments. While multicast is not currently integrated into LoRaWAN’s A and C classes, proposals exist for its utilization in the B class [14]–[16]. Although the implementation of multicast falls beyond the scope of this work, the multicast feedback idea significantly enhances network adaptability and responsiveness by enabling more efficient collective control over network behavior.

Initially, we evaluated our approach in a single gateway setup, focusing on simplicity, ease of implementation,

and proof-of-concept validation. While this context yields promising outcomes, it does not fully leverage LoRaWAN’s strength—its spatial diversity. Given that realistic deployments are inherently multigateway, the applicability and performance of DiPTC in such environments remain unexplored. Thus, our objective is to investigate DiPTC in a multigateway setup, exploring two feedback reception strategies: synchronous, where all nodes receive feedback simultaneously, and round-robin, where only specific nodes receive the feedback.

III. CHARTING MULTIGATEWAY TRAFFIC CONTROL STRATEGIES

In this section, we outline the assumptions and explain our contributions.

A. Assumptions

In our work, we base our analysis on the following key assumptions. We consider a network with multiple gateways (M) and an unspecified number of connected nodes (N). We also assume that the M gateways transmit the feedback message synchronously. Downlink messages are simplified to binary format, indicating whether traffic needs to be increased (1) or reduced (0).

TABLE I: Simulation parameters.

Algo.	DiPTC	LoRaWAN
N	150	150
M	3	3
K	10	10
ΔT	1 min	1min
x_I	0.5	-
x_D	0.5	-
P_{adapt}	0.06	-
$1/\lambda$	-	15 min
$Simtime$	1 year	1 year

B. Feedback transmission strategies

To illustrate our approach, we consider an example scenario of an LPWAN network consisting of $N = 5$ nodes and $M = 3$ gateways, where nodes are allowed to transmit data (see Fig. 1, step *a*). At the end of the designated time period ΔT , the network server compares the actual number of received messages, denoted as k , with a predefined objective K . If k is different from K , the network server initiates a feedback message intended for the M gateways. Subsequently, the gateways relay the feedback message to the network nodes after receiving it from the network server.

In this work, we propose employing two different strategies to send the feedback message to the nodes: the synchronous and the round-robin strategies (see Fig. 1). In the following explanations, we will focus on the scenario where the network server receives more messages than desired ($k > K$) and subsequently sends a message instructing nodes to reduce their traffic intensity. The opposite scenario, where the network receives fewer messages than required ($k < K$), can be easily deduced from this explanation by reversing the logic.

Synchronous strategy In the synchronous strategy, depicted in Fig. 1, step *b*₁, the three gateways send simultaneously the feedback message. In this case, the feedback message

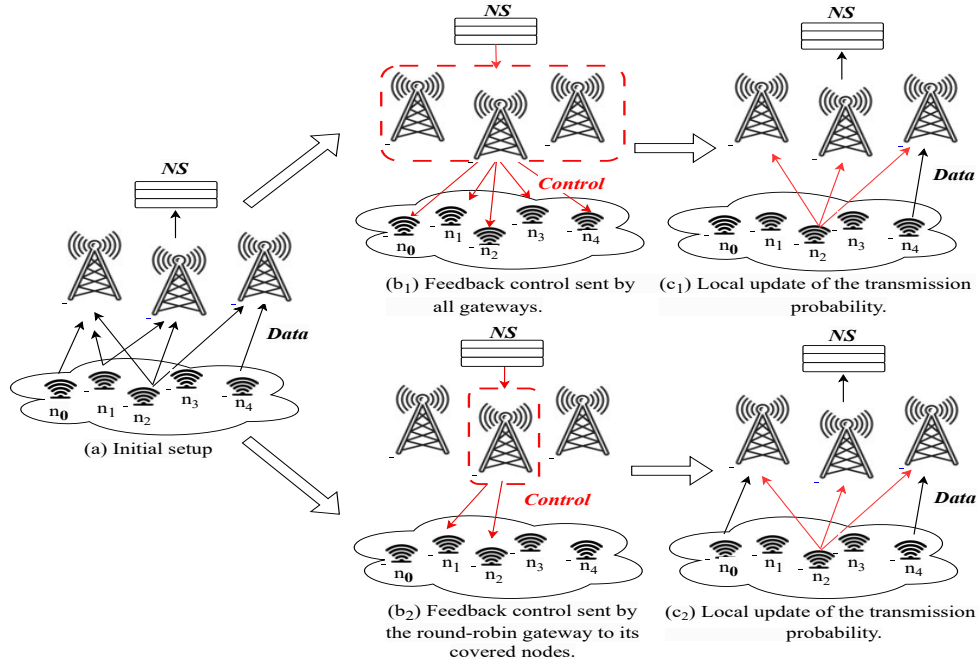


Fig. 1: Feedback transmission strategies in multigateway DiPTC. The red color denotes feedback transmission and transmission with the newly adapted traffic intensity.

serves a primordial purpose; to encourage a decrease in the uplink traffic intensity for each node, consequently allowing them to transmit fewer messages. Upon receiving the feedback message, each node employs the DiPTC protocol to compute, update, and reduce the number of messages to be sent locally, as shown in Fig. 1, step c_1 , with only two nodes transmitting messages (n_2 and n_4).

Round-robin strategy In the round-robin strategy, only one gateway transmits the feedback message at a time (see Fig. 1, step b_2). This message is received exclusively by nodes within the coverage of that particular gateway; in our example, two nodes receive it (n_1 and n_2). We select the transmitting gateway using a round-robin method, where with each time interval ΔT , the next gateway in line sends the feedback message. Upon receiving the feedback message, the two nodes adjust their traffic intensity locally, guided by the feedback. After this adjustment, one node continues transmitting (n_2) while the other reduces its traffic to the point of ceasing transmission (n_1) and those outside the coverage area maintain their prior transmission pattern (Fig. 1, step c_2).

As detailed above the round-robin method distributes tasks sequentially among gateways, balancing workload and respecting duty cycles. This helps prevent device collisions but may increase delay for remote devices. Conversely, the synchronized algorithm enables all gateways to transmit at once, ensuring messages reach all nodes simultaneously, a crucial feature for applications requiring high precision. However, this method demands meticulous synchronization of gateways, which can be challenging and resource-intensive. The intuition behind using these approaches lies in taking advantage of their unique strengths: round-robin for its simplicity and efficiency

in handling gateway duties, and synchronized transmission for its capability to deliver simultaneous messaging.

IV. SIMULATION SETUP

In this section, we present the simulation model, where we describe the scenarios and network parameters, introduce the benchmark protocol for comparison, and outline the performance evaluation criteria.

A. Simulation model

While our solution can be applied to any LPWAN technology, we choose LoRaWAN to simulate and evaluate the performance of our protocol. To implement our protocol, we use LoRaSim [17] a discrete event simulator based on SimPy, which allows simulating collisions, the capture effect, and interference in LoRaWAN. We enhance LoRaSim with a broadcast downlink model and a battery depletion model.

- LoRaSim does not implement downlink communication. We modified the simulator (1) by adding a downlink broadcast from the gateway to all the nodes, and (2) by modeling the reliability of the downlink through a random variable that follows a Bernoulli distribution of parameter p_{DL} . For the uplink and collision models, we use the ones in [17].
- LoRaSim does not implement the energy consumption of the nodes. We modify the simulator by adding the energy consumption model described in [18]. The energy consumed E_c after transmitting m messages for each node n , depends on the time on air TOA , the power consumed in the receiver mode P_{wRx} and the power consumed in the transmitter mode P_{wTx} .

$$E_c = TOA * (P_{wTx} * m + P_{wRx}) \quad (1)$$

TABLE II: Synchronous DiPTC, round-robin DiPTC, and LoRaWAN performance.

Protocol	150 Nodes			300 Nodes			500 Nodes		
	μ_c	PDR	t_l	μ_c	PDR	t_l	μ_c	PDR	t_l
Synchronous	96.87%	0.99	35258min	97.54%	0.979	49450min	97.89%	0.974	87746min
Round-Robin	94.70%	0.987	35809min	96.75%	0.958	55450min	97.98%	0.938	94746min
LoRaWAN	0.99%	0.90	47500min	1.2%	0.87	48227min	3.5%	0.85	49120min

B. Scenario and network parameters

This work evaluates the performance of our approach, DiPTC, against LoRaWAN in simulated scenarios with three central gateways and multiple scattered nodes. We focus on intensive traffic to observe operational adaptation, aiming to assess DiPTC’s performance under high network demand. Using a network of 150 nodes requiring 10 measurements per minute, we fix adaptation parameters at ($x_I = 0.5$, $x_D = 0.5$, $P_{adapt} = 0.06$). Moreover, we expand our analysis by scaling node counts from 150 to 300 and 500 to assess spatial scalability. Analyzing these performance measures yields insights into DiPTC’s adaptability and effectiveness in high-demand scenarios, primordial for real-world deployment considerations.

C. Benchmark protocol: LoRaWAN

LoRaWAN uses a Poisson distribution to model node transmissions [17], accommodating IoT’s asynchronous nature. The mean inter-arrival rate ($1/\lambda$) reflects the average transmission attempt rate, primordial for energy-efficient IoT communication. Regulating ($1/\lambda$) for a fair comparison with DiPTC considers factors such as time period, desired measurements, and network size, where λ is computed as the product of the ratio of time period to desired measurements and the number of nodes in the network ($\lambda = \frac{\Delta T}{K} \times N$). Table I, summarizes the values of the different parameters used in our simulation.

D. Evaluation criteria

To offer a thorough overall performance assessment of our proposed synchronous and round-robin DiPTC protocols in a multigateway setup, we use key metrics such as:

- **Success rate μ_c** : measures the number of times the base station receives exactly the K required measurements per period ΔT .
- **Packet Delivery Ratio PDR**: measures the ratio of successfully delivered messages to the total number of messages sent.
- **Network lifetime t_l** : measures the time the network can support the application requirements (i.e., the nodes can send the K required measurements per period ΔT before the exhaustion of their battery).
- **Error Frequency**: measures how accurately the network transmits measurements. It quantifies the discrepancy between the required K and the actual number of messages sent within a specified time interval ΔT . A lower error frequency indicates a more precise protocol capable of consistently transmitting the desired number of messages at regular intervals.

- **Transient Regime Duration Frequency**: measures the frequency of the periods when the network fails to send the required K messages within each time interval ΔT . Analyzing these transient regimes provides insights into the network’s dynamic behavior and its ability to adjust to changing conditions.

V. RESULTS ANALYSIS

To assess the effectiveness of our protocol, we initially conduct an overall evaluation, comparing key metrics such as network lifetime, success rate, and packet reception rate for both transmission strategies and LoRaWAN. Following this broad assessment, we dig into a more detailed analysis, focusing on the error frequency and transient regime duration frequency metrics explained earlier.

A. Overall Performance Evaluation

Table II compares the overall performance evaluation metrics, including network lifetime, packet reception rate, and success rate, across varying numbers of nodes for round-robin, synchronous DiPTC, and LoRaWAN. Compared to LoRaWAN, both transmission strategies’ success rate increases with the number of nodes in the network. The DiPTC protocol’s ability to dynamically control traffic intensity ensures efficient resource usage, mitigates congestion, and enhances communication reliability, thereby increasing the success rate as the number of nodes in LPWANs grows. When comparing the round-robin strategy to the synchronous approach, the latter shows a slightly higher success rate. This is because the likelihood of sending exactly 10 messages per minute increases since each node receives feedback messages and adjusts its traffic accordingly.

Note that, the packet reception rate drops as the number of nodes in the network increases for the three protocols. The probability of a collision increases with the number of nodes, which has a detrimental impact on the packet reception rate. In the round-robin strategy, nodes lose their feedback message if they are not covered by the chosen gateway. Due to this feedback message loss, round-robin DiPTC has a slightly lower packet reception rate than the synchronous strategy. The node keeps on trafficking in the same manner as it did during the prior period when it loses its feedback message, which raises the probability of a collision and therefore reduces the packet reception rate.

In both transmission strategies, we observe an increase in network lifetime as the number of nodes in the network grows, that is not the case for LoRaWAN. The inherent adaptability of DiPTC to varying network conditions and application demands

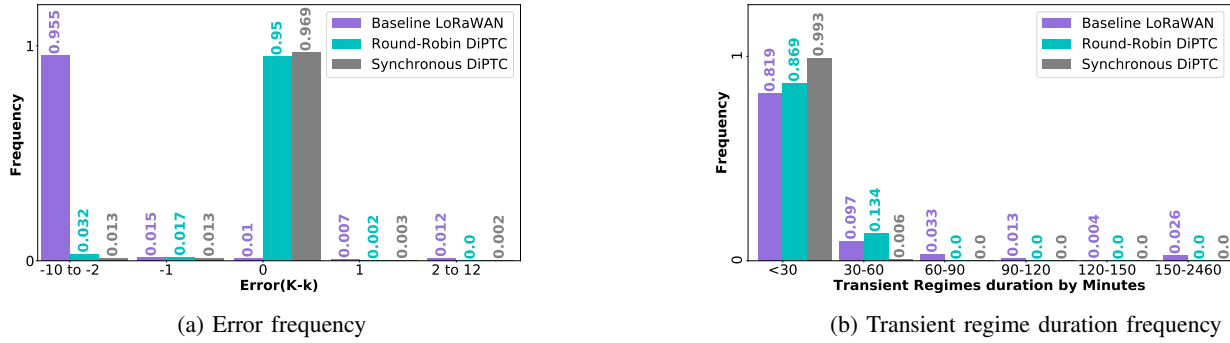


Fig. 2: Comparison of error frequency and transient regime duration frequency for LoRaWAN, round-robin, and synchronous DiPTC.

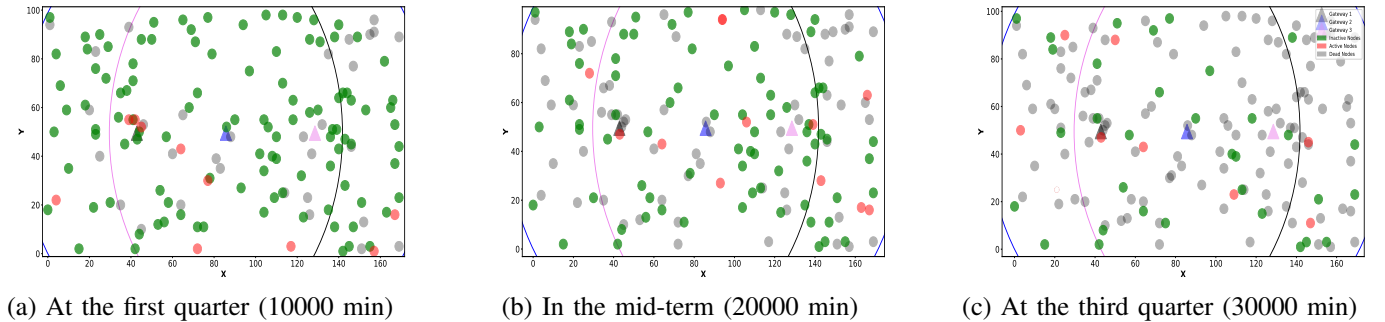


Fig. 3: Spatial distribution of active nodes in the round-robin DiPTC, 43200 min (1 month).

contributes to the observed increase in network lifetime as the number of nodes in the network grows, highlighting the effectiveness of adaptive traffic control mechanisms in LP-WAN environments. In contrast, LoRaWAN's lack of dynamic adaptation prevents network lifetime from increasing with the number of nodes due to limited bandwidth, static parameters, and inefficient energy consumption. Compared to the synchronous strategy, the round-robin approach demonstrates a longer network lifetime. This is because in round-robin transmission, there are nodes that cannot receive data due to the chosen gateway coverage, so they cannot adapt their traffic, and those nodes gain energy, which keeps the network alive longer than in Synchronous DiPTC, where all nodes receive the feedback message.

B. In-Depth Evaluation

Fig. 2 compares error frequency and transient regime duration frequency for round-robin, synchronous DiPTC, and LoRaWAN. Fig. 2a, illustrates the application error over time. A zero application error signifies that the application precisely received 10 measures per minute. This indicates that both round-robin and synchronous DiPTC have a higher frequency of zero application errors compared to LoRaWAN. Meanwhile, larger values of application errors are less frequent in both round-robin and synchronous DiPTC but more common in LoRaWAN. This suggests that our protocols are better at meeting application demands consistently than LoRaWAN.

This difference arises because LoRaWAN lacks a control mechanism. Also, synchronous DiPTC is better at meeting application needs compared to round-robin DiPTC. This happens because in round-robin, not all nodes get the feedback message, so they keep transmitting in the same way as before, slowing down the convergence process.

Fig. 2b shows the frequency duration of transient regimes, indicating that LoRaWAN experiences more frequent long transient regimes compared to round robin and synchronous DiPTC. Moreover, round-robin DiPTC shows more medium-long transient regimes than synchronous DiPTC due to gateway coverage issues causing delays in message reception, which extends the transient regime duration.

C. Distributed load balancing feature

To ensure that DiPTC does not introduce spatial bias in data collection, particularly in round-robin transmission mode, we present Figure 3, depicting node activity at different intervals during DiPTC round-robin simulation. Each node is covered by at least two gateways, and active nodes are shown in green. Results indicate messages originate from various locations across the intended area, suggesting spatial load-balancing akin to the mono-gateway scenario [7]. Identical parameter configurations and spatial distributions are used for both round-robin and synchronous DiPTC simulations. The observations hold true for synchronous DiPTC, with no discernible differences noted.

D. Discussions

The use of round-robin and synchronous DiPTC protocols shows robust convergence outcomes, proving their effectiveness in high-density networks and high-traffic scenarios compared to LoRaWAN. This enhances LPWAN performance by adapting to various application demands within a multigateway environments employing traffic management. The stable adaptation protocol ensures reliable convergence towards required measurements, maintaining low absolute error margins, low overhead, and collision rates, while balancing network lifetime, success rate, and packet reception rate.

In LPWANs, downlink communication is often constrained by a duty cycle, limiting the time for data transmission. In synchronous transmission, all M gateways transmit simultaneously, leading to M times more downlink traffic compared to round-robin strategy where only one gateway transmits at a time resulting in significantly lower radio interface congestion (by a factor of M or more). This reduced congestion is due to the sequential nature of round-robin transmission. Also, high downlink traffic in the synchronous strategy can lead to collisions and reduced reliability, especially in dense areas. Additionally, round-robin transmission better adheres to duty cycle regulations, allowing for more efficient downlink channel usage. Also using round-robin DiPTC diversifies data collection by involving nodes from different collecting areas, conserving network energy and extending its lifetime, despite the increase in collision probability. However, the nodes and gateway distribution must be optimized if not it may introduce unevenly distributed traffic, increasing latency for distant nodes. Choosing between synchronous and round-robin DiPTC involves weighing these factors to meet specific network and application priorities.

VI. CONCLUSION

In this work, we introduce an approach to traffic management in multigateway LPWAN environments, which differs from traditional methods by incorporating feedback mechanisms via binary control messages distributed by the gateway(s). These messages allow nodes to dynamically adjust their traffic intensity, adapting to the diverse requirements of various applications in a given area, irrespective of network topology. We investigate two feedback reception strategies: synchronous, where all nodes receive feedback, and round-robin, where only selected nodes receive feedback, demonstrating the versatility and adaptability of our strategy. Performance evaluation demonstrates that DiPTC performs exceptionally well in both synchronous and round-robin transmission strategies, achieving convergence of application requirements while minimizing collision risks within acceptable delays. However, choosing between these strategies requires careful consideration of tradeoffs, including network lifetime, success rate, and packet reception rate. Each transmission strategy offers distinct advantages and compromises, emphasizing the importance of selecting the strategy that aligns with the specific objectives and constraints of the LoRaWAN application. Importantly, our findings indicate that

both synchronous and round-robin implementations of DiPTC outperform conventional LoRaWAN approaches, highlighting the effectiveness of our proposed traffic control protocol in improving the overall performance and efficiency of LoRaWANs in multigateway scenarios. Despite its simplicity, the round-robin method can result in uneven traffic distribution, causing higher latency for nodes located further away. Moreover, synchronous transmissions may lead to collisions and decreased reliability, particularly in dense environments. Alternative approaches such as multi-channel communication, enabling parallel transmissions to reduce collisions, and machine learning optimization, offering efficiency gains, may introduce complexity and scalability challenges.

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