LoRa Optimal Channel Selection using Game Theory

Soham Kadtan*, Biraja Nanda Mohanty*, Alekhya Gorrela*, Nikumani Choudhury*
Arj Patel*, Ayush Patel*, Shobhan Dash*, Sai Charan*, Eshaan Sudan*, Chetan Surya Reddy*
* Dept. of Computer Science & Information Systems, Birla Institute of Technology & Science, Pilani, Hyderabad, India
. Email: {h20231030094, h20231030070, p20220103, nikumani}@hyderabad.bits-pilani.ac.in

***Abstract*—Low-power wide-area networks (LPWAN) have substantially improved the Internet of Things (IoT). LoRaWAN is a potential technology for IoT applications because it uses low-power, long-distance communication and offers excellent availability with low energy consumption. LoRaWAN power consumption can be reduced using the pure Aloha protocol at the MAC level. Optimizing orthogonal transmission parameters is still a major difficulty for enhancing network performance, even though they reduce packet loss and prevent collisions, especially in dynamic and heterogeneous networks. However, the challenge of random channel selection in LoRaWAN communication often leads to inefficient resource utilization and degraded network performance. This paper proposes a novel game-theoretic approach for optimal channel selection in LoRaWAN networks. Our method leverages real-time Received Signal Strength Indicator (RSSI) data and a non-cooperative game theory model to dynamically select channels, thereby improving throughput and reducing packet loss. Through simulations, we demonstrate that our proposed mechanism outperforms existing approaches in terms of throughput, packet delivery ratio, and energy efficiency, particularly under heavy and dynamic traffic conditions. This work offers a significant advancement in enhancing the scalability and reliability of LoRaWAN networks, paving the way for more efficient IoT communications.**

***Index Terms*—LoRaWAN, Industrial Internet of Things, Game Theory, Optimal Channel Selection, RSSI.**

I. Introduction

In today's world, the Internet of Things (IoT) is essential, connecting devices through battery-powered sensor networks. Choosing the right communication technology to manage and maintain service quality in IoT is important because of its features [1]. LPWANs represent a transformative force in the realm of communication technology, offering a compelling solution to the challenges posed by the increasing proliferation of IoT devices and applications. The ability of LPWANs to provide extensive radio coverage at minimal data costs has revolutionized how sensor nodes are connected and communicate over long distances. This capability is particularly valuable in scenarios where traditional wireless WANs fall short, as LPWANs excel in balancing the need for efficient data transmission with energy conservation. In the context of smart cities, LPWANs play a pivotal role in enabling various innovative applications that enhance urban infrastructure and services. From optimizing agricultural practices through precision farming techniques to streamlining traffic flow and parking management with smart solutions, LPWAN technology has become instrumental in driving sustainable urban development. By facilitating real-time monitoring of environmental parameters and enabling seamless communication in home automation systems, LPWANs empower cities to become more efficient, responsive, and environmentally friendly.

The versatility of LPWAN technology is further underscored by the distinct operational modes of LoRaWAN devices across different classes [2]. Class A devices, with their periodic data transmission and short listening windows, are well-suited for applications requiring intermittent communication with minimal power consumption. Class B devices, featuring scheduled receive windows, enhance the efficiency of bidirectional communication, making them ideal for scenarios where timely data exchange is essential. Meanwhile, with their continuous listening windows, Class C devices offer immediate downlink reception capabilities, catering to applications that demand constant connectivity and responsiveness. They demonstrate their adaptability and scalability in meeting the evolving demands of the digital landscape by offering a diverse array of device classes tailored to varying IoT application needs. As the adoption of IoT devices continues to expand across industries and sectors, the role of LoRaWAN in providing reliable, cost-effective, and energy-efficient connectivity solutions will only grow in significance [3]. The seamless integration of LoRaWAN technology into the fabric of modern communication infrastructure is poised to drive innovation, enable new possibilities for smart applications, and pave the way for a more connected and intelligent future.

A. Motivation

In IoT communication, the issue of random channel selection poses a significant challenge, resulting in inefficient use of resources and degraded performance. To address this issue, we are using an online algorithm based on the game's theoretical approach, which is used to select the optimal channel from the available channels in real-time. Before selecting the optimal channel, game theory considers some factors such as signal strength, the utility of each channel, and historical data transmission success rates. By continuously monitoring this algorithm, it dynamically selects the channel that maximizes throughput and minimizes packet loss. Once the optimal channel is selected, data packets are routed through this channel, ensuring efficient transmission and reliable communication over the network.

B. Contribution & Organization

In this paper, we propose a novel technique to select optimal channel selection in the LoRa network. This is achieved by using a game theoretic approach, which is based on online algorithms. To determine the signal intensity from each sensor device, the gateway first evaluates the RSSI from all sensors. Every sensor device simultaneously assesses the RSSI to ascertain the strength of the signal it gets from the gateway or other sources. The proposed technique guarantees that the sensors independently select the optimal channels based on local RSSI data. The contributions of the paper are summarized below.

1) Development of an optimal channel selection mechanism to ensure efficient transmission and reliable communication over the network.
2) A non-cooperative game theory approach is used to dynamically select the optimal channel based on signal strength, the utility of each channel, and historical data transmission success rates.
3) Performance comparison with existing work shows the proposed mechanism improves several QoS measurements under heavy and dynamic traffic loads.

The paper is organized into the following sections: Section II presents the literature work on the LoRaWAN channel selection and performance measurements. The network model is described in Section III. Section IV presents the proposed channel selection mechanism. In Section V, the experimental results are shown. Finally, Section VI concludes the paper.

II. Related Work

A scalability analysis of the LoRa Network for SNR-based SF Allocation Scheme is described in [1]. SFs are generally allocated using equal-interval-based (EIB) and equal-area-based (EAB) SF allocation systems, which take into account the gateway's distance. In [4], the author has provided a framework to enhance the scalability and performance of the LoRaWAN network. This framework schedules devices based on their QoS requirements, network density, and contextual data. The availability of resources and the best strategies for managing them in LoRaWAN networks have come under scrutiny due to the vast number of devices interacting with one another in Internet of Things applications. LoRa networks face the problem of scalability when they connect thousands of nodes that access the shared channels randomly. The authors in [5] suggest a novel method for enhancing LoRaWAN scalability and reliability using lightweight scheduling. An optimal channel selection in multichannel wireless sensor networks based on online decision and offline learning is examined in [6]. In order to reduce access point overhead and increase network deployment flexibility, they proposed a hybrid architecture channel selection strategy that combines centralized and distributed approaches. The collision resolution protocol for the delay and energy-efficient LoRa networks has been introduced in [7]. When there are collisions, the perceived rate is further decreased by packet loss and retransmissions. First, the author suggested a decoding technique that resolves many superposed LoRa signals in order to lessen the negative effects of collisions. Second, they create a complete MAC protocol that makes collision resolution possible.

In [8], a new Medium Access Control (MAC) protocol called FCA-LoRa is presented together with a unique scheduling approach that enhances collision avoidance in LoRa wide-area networks by leveraging fairness. Low energy consumption and enough throughput are guaranteed by using LoRaWAN technology's low-power but long-range communication channels. However, the reliability of the technology is compromised by a significant probability of packet collisions resulting from the initial scheduling procedure of LoRa. The authors in [9] presented a novel, lightweight timeslot scheduling system that satisfies the needs of huge Machine Type Communications on LoRaWAN networks, taking into account the various channels and quasi-orthogonal data rates in addition to traffic periodicity. A wireless paradigm known as mMTC (Massive Machine Type Communications) that focuses on traffic carried by several inexpensive, low-power, infrequently sending devices is presented. The authors of [10] suggested the RCA LoRa, a new MAC protocol, to increase collision avoidance and dependability in LoRa wide-area networks. Low energy consumption and enough throughput are guaranteed by using LoRaWAN technology's low-power but long-range communication channels. However, the reliability of the technology is compromised by a significant probability of packet collisions resulting from the initial scheduling procedure of LoRa. The author of this paper [11] presented the LIDS (Lightweight Dynamic Scheduling) approach for Massive LoRa-based IoT Systems enabled by 6G. The suggested mechanism optimizes power usage to meet the required level of QoS criteria, such as throughput and latency to reduce data transmission loss due to collisions. In order to accommodate devices with varying SFs, the current synchronization and scheduling algorithms use one superframe with set time slots to transmit synchronization messages at random. This phenomenon can limit the scalability of LoRaWAN networks by causing collisions, idle slots, and inefficient energy use. In [12], the authors suggested a dynamic Multi-Frame Multi-Spreading Factor (MFMSF) scheduling method using a slotted synchronization strategy in order to mitigate the aforementioned issues. However, the prior work done in this area suffers from high overhead and does not focus on dynamic and adaptive network and channel conditions. Therefore, there is a requirement for a lightweight mechanism to improve the performance of the LoRaWAN networks. In this paper, we propose an optimal channel selection mechanism that results in improved QoS performance.

III. Network Model

The network model considered in this paper has been shown in Fig. 1. This model represents a detailed network server system with a gateway and multiple sets of sensor nodes, each performing specific functions in data transmission and

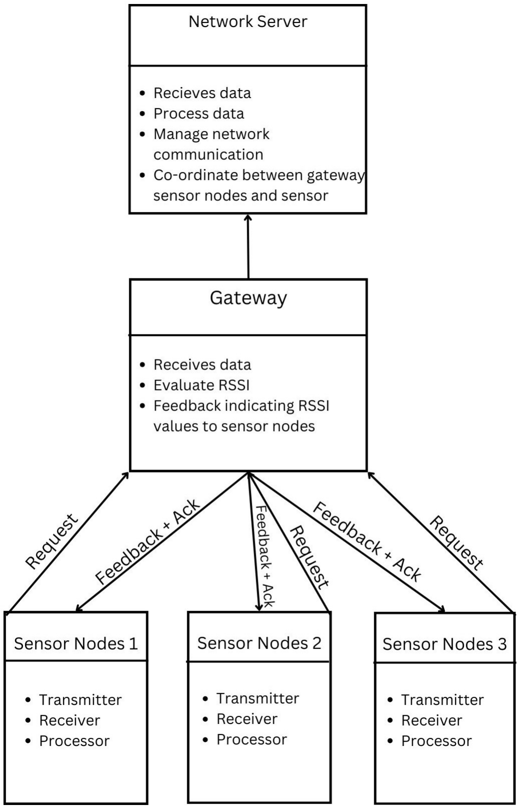


Fig. 1. LoRaWAN Working

network management. Here is an in-depth breakdown of the components and interactions depicted in the diagram:

1. Network Server:

Positioned at the top of the diagram, the network server is the central hub for data processing, network management, and communication coordination between the gateway and sensor nodes. Functions of the network server: Processes incoming data from the sensor nodes. Manages network communication protocols and data flow. Coordinates interactions between the gateway and sensor nodes for seamless operation.

2. Gateway:

The gateway acts as a bridge between the network server and the sensor nodes, facilitating data exchange and feedback mechanisms. The Key functions of the gateway: Receives data packets from the sensor nodes for further analysis and processing. Evaluate the RSSI values to assess signal quality and reliability. Provides feedback to the sensor nodes based on the RSSI values, enabling adjustments in transmission parameters for optimal performance.

3. Sensor Nodes:

The diagram showcases three sets of sensor nodes (Sensor Nodes 1, Sensor Nodes 2, Sensor Nodes 3) connected to the gateway, each comprising essential data transmission and reception components. Functions of the sensor nodes: Transmitter: Sends data packets to the gateway for processing and analysis. Receiver: Receives feedback and acknowledgements from the gateway regarding data transmission and signal quality. Processor: Manages data processing tasks within the sensor nodes, ensuring efficient operation and communication with the gateway.

4. Feedback and Acknowledgment:

Feedback and acknowledgement mechanisms indicate a robust communication protocol within the network, allowing nodes to confirm successful data transmission, receive feedback on signal strength, and adjust their operations accordingly.

5. Request:

The diagram includes request arrows, suggesting a bidirectional communication flow where nodes can request specific actions, data, or responses from other components in the network. In summary, the detailed network server system architecture depicted in the image highlights the collaborative efforts of the network server, gateway, and sensor nodes in ensuring seamless data transmission, signal evaluation, and feedback mechanisms for efficient network operation and communication in IoT or sensor network applications.

IV. PROPOSED WORK

Game theory is a mathematical framework that analyzes strategic interactions between rational decision-makers. In network algorithms, game theory can be applied to optimize channel selection, resource allocations, and decision-making processes. Optimal channels involve choosing the best communication channel based on signal strength, interference, and data rate. Selecting the optimal channel helps improve network performance, reduce packet loss, and enhance communication reliability. RSSI is a metric that quantifies the strength of the signal received by a receiver from a transmitter. RSSI is used to assess the signal quality, determine link reliability, and optimize communication parameters in wireless networks. In a sensor network, multiple sensors are deployed to monitor and gather data from various environments. These sensors communicate wirelessly with a central gateway or a base station to transmit the collected data. Efficient communication is crucial in such networks to ensure timely and reliable data transmission while conserving energy and bandwidth. Wireless communication channels can be subject to various factors that affect transmission quality, such as signal strength, interference, noise, and environmental conditions. Received Signal Strength Indicator (RSSI) is a commonly used metric to quantify the strength of the signal received by a receiver from a transmitter. It provides valuable information about the quality of communication between nodes in a wireless network.

The proposed algorithm 1 uses a non-cooperative game-theoretic approach to optimize channel allocation in a LoRaWAN network. To determine the signal intensity from each sensor, the gateway first evaluates the RSSI from all sensors. Every sensor simultaneously assesses the RSSI to ascertain the strength of the signal it gets from the gateway or other sources. Subsequently, the algorithm runs through every network sensor, sending a request to the gateway from each sensor. This request could be for channel allocation or the

RSSI readings from the sensor. The gateway provides RSSI input to the sensors after each one has sent its request; this data usually includes details about the channel conditions and signal strength. After that, the algorithm goes into a while loop, which keeps running until a specific condition is satisfied or goes on forever. Each sensor in this loop determines how useful it could be for every open channel, calculating a utility function for each channel based on the RSSI data. Using the signal strength as a guide, this utility function helps assess a channel's suitability. The method determines whether every sensor may increase its usefulness by changing channels. The loop breaks if no sensor can improve its utility, meaning the ideal channel allocation has been reached. Ultimately, each device chooses the channel that optimizes its usefulness, resulting in a successful channel selection procedure that reduces interference and enhances network performance. To achieve a globally optimized network design without centralized control, our game-theoretic method guarantees that sensors independently select the optimum channels based on local RSSI data.

A. Proposed Algorithm

Algorithm 1: Non-cooperative Game for Channel Selection

Gateway evaluates the RSSI
Sensor i evaluates the RSSI
for $i = 1$ to n **do**
  Sensor i transmits request to Gateway
end for
Sensors receive RSSI feedback from Gateway
while True **do**
  for $i = 1$ to n **do**
    for $k = 1$ to K **do**
      Calculate utility function $u_{i,k}$ for channel k based on RSSI
    end for
  end for
  Break if no sensor can improve its utility by switching channels
end while
Each sensor selects the channel that maximizes its utility

Non-cooperative games model scenarios where players act independently to maximize their own utility or payoff without cooperating or making binding agreements with other players. In wireless channel selection, each node or sensor can be viewed as a self-interested player trying to choose the best available channel to maximize performance metrics like throughput or single quality.

Some key aspects of non-cooperative channel selection games include:

1. Utility Function: Each player(node) has a utility function that quantifies the benefit or cost of selecting a particular channel based on factors like RSSI, interference, congestion, etc. Nodes aim to maximize their utility.
2. Strategy Space: The set of available channels forms the strategy space for each player. Nodes can choose to transmit on any of the available channels.
3. Best Response: Given the current channel of other nodes, each node tries to find its best response - the channel that maximizes its utility against the current strategies of others.
4. Nash Equilibrium: A Nash equilibrium is a stable state where no node can further improve its utility by unilaterally deviating from its current channel choice, given the selections of other nodes. The non-cooperative game algorithm iteratively lets sensor nodes evaluate their utilities across channels and switch to the best response channel until convergence to a Nash Equilibrium is achieved.

TABLE I
NS3 SIMULATION PARAMETERS

Simulation Parameters	Values Considered
Number of end-devices	105
Duty Cycle	0.01
Packet Length	20 bytes
Preamble Length	8 bytes
Frequency	868 MHz
Bandwidth	125 KHz
Coding rate	4/5
Path loss exponent	4
Spreading Factors	{7,8,9,10,11,12}
Transmission Powers	{2,5,8,11,14} dBm

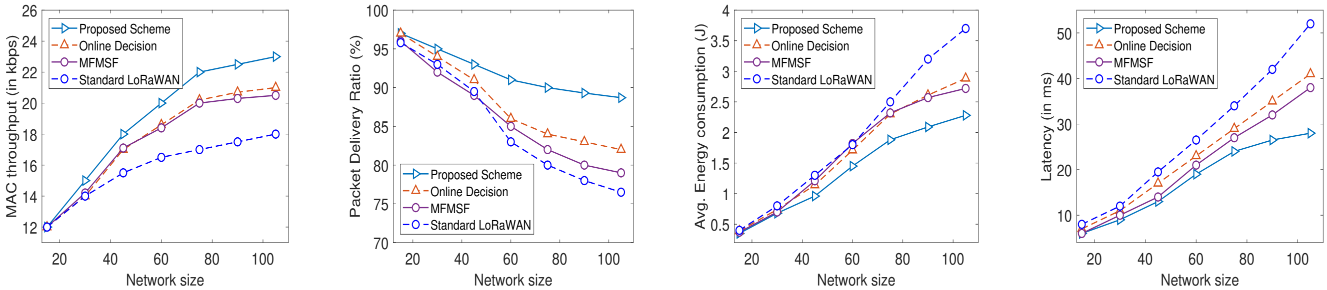
V. EXPERIMENTAL RESULTS

In this section, the performance of the proposed mechanism is evaluated and compared with the other closely related schemes like Online Decision algorithm [6], MFMSF [12] and the standard LoRaWAN. The performance metrics for evaluating the proposed scheme are 1) Throughput, 2) Packet Delivery Ratio, 3) Latency, and 4) Average Energy Consumption.

A. Simulation Setup

We consider a network topology, as shown in Fig. 1, comprising numerous end devices and gateways. This network occupies a spatial expanse of 1000×1000 m. We introduce additional LoRa end devices or gateways to expand the network's capacity. Simulations are performed on the ns3 network simulator, leveraging the LoRa module. Detailed simulator parameters and configurations can be found in Table I. The simulations are averaged over 30 different runs.

1) Throughput: The proposed game-theory approach improves the overall throughput of the network by choosing an optimal channel for transmission using local RSSI information. This results in efficient transmissions with fewer collisions with other transmissions to the LoRa gateway. From Fig. 2(a), it can be observed that the proposed mechanism results in higher throughput compared to other related schemes. This is because the proposed mechanism incorporates the RSSI feedback from the Gateways, resulting in faster convergence in computing the optimal channel.



(a) (b) (c) (d)

Fig. 2. (a) Throughput, (b) Packet Delivery Ratio, (c) Average Energy Consumption, and (d) Latency.

2) Packet Delivery Ratio: The selection of an optimal LoRa channel enhances the Packet Delivery Ratio by minimizing interference, balancing network load, and optimizing propagation conditions. This ensures clearer communication paths, reduces packet collisions, and enables effective Adaptive Data Rate adjustments, leading to more reliable data transmission. Fig. 2(b) depicts that the proposed scheme results in an enhanced packet delivery ratio. An optimal channel results in lower probability of collisions, thereby enhancing the PDR of the proposed mechanism.

3) Average Energy Consumption: Energy consumption is one of the primary design goal any low-power communication technology. The proposed scheme requires an insignificant energy in computing the utility function, which is O(n^2) in terms of computation. The overhead in transmission that results in energy consumption is one extra message sent by the end-devices to the LoRa Gateway requesting RSSI feedback. Compared to the other considered schemes, this is low as presented in Fig. 2(c).

4) Latency: Latency is a crucial Quality of Service (QoS) metric for LoRaWAN. Although, it supports relaxed latency requirements from applications, the proposed scheme aims to reduce latency arising from re-transmission of messages. This can occur due to frequent collisions if messages are transmitted in a congested channel. From Fig. 2(d) it can be inferred that proposed mechanism has least latency as it able to quickly compute an optimal channel for the end-devices to transmit.

B. Testbed Implementation

A proof-of-concept showcasing the proposed implementation of the proposed was done in a testbed configuration as shown in Fig. 3) employed an ESP-32 microcontroller paired with an RFM95W radio transmitter, operating at 868MHz, to function as the end device. The gateway component was realized using a Dragino PG 1302 Concentrator connected to a Raspberry Pi 4. This concentrator efficiently aggregates the LoRa signals, while the Raspberry Pi facilitates data transmission to the network server. We considered ten end devices, one LoRa gateway and one LoRa NS. The primary objective is to measure the performance of the proposed mechanism in a dynamic and heterogeneous environment, as illustrated in Fig. 4(a) and Fig. 4(b).

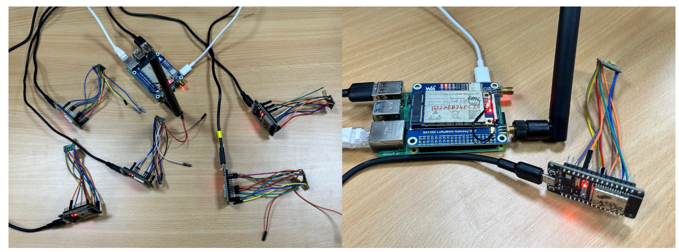
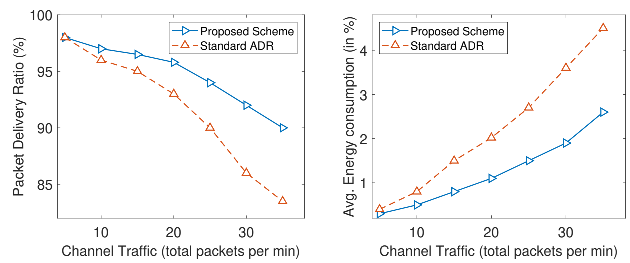


Fig. 3. Testbed Setup



(a) (b)

Fig. 4. Performance of the Proposed Scheme under varying channel traffic

VI. Conclusion & Future Work

In this paper, we have proposed a novel channel selection mechanism for LoRa networks, leveraging a game-theoretic approach that enables each sensor device to independently select the optimal communication channel based on local RSSI data and historical transmission success rates. The proposed scheme effectively reduces network congestion and minimizes latency, demonstrating significant improvements in QoS metrics such as throughput, packet delivery ratio, and energy efficiency under varying network conditions. The testbed implementation and performance analysis confirm the robustness and scalability of the proposed mechanism, making it a viable solution for dynamic and dense LoRaWAN environments.

While the proposed mechanism has shown promising results, several areas for future research remain. Firstly, integrating machine learning techniques to predict network conditions and further optimize channel selection could enhance the adaptability and efficiency of the system. Secondly, expanding the testbed to include a more extensive network with heterogeneous devices and traffic patterns will provide deeper insights into the scalability and reliability of the proposed approach.

VII. Acknowledgement

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