# ENERGY-EFFICIENT ADAPTIVE DATA RATE OPTIMISATION SCHEME FOR LORAWAN

by

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# SUMMARY

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The Internet of Things (IoT) is a paradigm that has revolutionised wireless network technologies worldwide owing to its low power consumption, low cost of deployment, long-range communication, and its ability to accommodate a substantial number of end devices (EDs). Many industries have adopted the use of IoT to improve decision-making, to function more efficiently, to automate various operations, and to minimise energy usage, thus helping in the reduction of greenhouse gas emissions. Among the IoT technologies, Low Power Wide Area Networks (LPWANs) perform a pivotal function in delivering efficient and scalable connectivity for this ever-expanding wireless communication system. One prominent LPWAN technology, Long Range Wide Area Network (LoRaWAN), has achieved widespread adoption attributable to its operation in the license-free sub-gigahertz frequency band, scalability, low bit rate, and energy efficiency.

LoRaWAN networks consist of low power end devices connected in a star of star topology to a network server (NS) through a gateway (GW), enabling seamless exchange of data connected through an IP-based back-haul connection. The EDs are energy-constrained as they are battery operated and can

be static or mobile and can sometimes be deployed in difficult-to-reach places, hostile or hazardous environments, necessitating a long battery life lasting several years. Wireless communication is the major source of energy consumption due to interference and packet collisions during packet transmission. It is essential to limit energy utilisation while maintaining the communication between the end devices and the gateway. This study focuses on enhancing energy efficiency in LoRaWAN networks to extend their network lifetime. An essential aspect of LoRaWAN is the Adaptive Data Rate (ADR) scheme, which optimises Quality of Service (QoS) requirements, battery life of EDs, and overall network performance. ADR manages transmission settings such as transmission power (TP), spreading factor (SF), bandwidth (BW), and coding rate (CR) based on the link budget. By optimising ADR, we can reduce airtime, increase network capacity, and improve energy efficiency.

Following the introduction of the LoRaWAN protocol in 2015 by the LoRa Alliance, there has been an absence of a standardised ADR implementation in the LoRa specification. It does not define the way the network server controls EDs regarding data rate adaptation. This has led to various ADR schemes being proposed by different vendors to accommodate diverse IoT scenarios and QoS requirements, posing challenges to reliability and suitability. A comprehensive literature review of existing ADR schemes highlighted their focus on scalability, throughput, and energy efficiency. The existing ADR schemes use different algorithms with different computational complexities to optimise the data rate, depending on the different goals such as coverage, received signal strength, congestion, capture effect and channel contention. The issue of energy consumption emerged as a major challenge.

To address this challenge, this research study proposed and implemented a novel fuzzy-logic-based adaptive data rate (FL-ADR) scheme for energy-efficient LoRaWAN communication. The impact of multiple GWs on a LoRaWAN network was investigated and the results were incorporated in implementing the LoRaWAN network using a ns-3 based LoRaWAN simulator, a widely used open-source simulation platform. The proposed FL-ADR scheme performance was contrasted with other state-of-the-art algorithms. Network performance was monitored by analysing the energy consumption, interference or collision rate, the packets that were lost because the GWs were busy, confirmed packet success rate (CPSR), the uplink packet delivery ratio (UL-PDR) and the energy efficiency of the algorithms. These metrics were evaluated for different data intervals and different network sizes. The simulation results showed that the proposed FL-ADR scheme achieved substantial energy savings of 43% and 14% compared to the standard Semtech-ADR algorithm and the ns-3-ADR algorithm respectively. Although the CPSR and UL-PDR dropped slightly, the FL-ADR algorithm exhibited

lower interference/collision rates, confirming its energy efficiency. The FL-ADR managed to efficiently adjust SF and TP despite a trade-off with CPSR and UL-PDR.

Additionally, we developed an SNR-based Spreading Factor Interference Rate controlled Adaptive Data Rate Algorithm, SSFIR-ADR, an ADR algorithm that improves packet delivery ratio by reducing packet collision and managing interference. We implemented multiple static end devices connected to a single gateway to resolve the packet delivery ratio challenge without compromising energy consumption. SSFIR-ADR decreases signal interference by managing the SF allocation to reduce the probability of simultaneous transmissions with the same spreading factor in a particular annulus region in the network using a stochastic approach. The performance was evaluated using three state-of-the-art algorithms. The simulation results demonstrated that our proposed approach exhibits an improved packet delivery ratio and interference rate compared to existing solutions. These significant results contribute to the novelty of the proposed adaptive data rate algorithms.

In conclusion, this research contributes valuable energy-efficient ADR algorithms for LoRaWAN communication, offering a practical and reliable solution to extend network lifetime and enhance overall network performance in IoT deployments.

# DEDICATION

This thesis is dedicated to the pillars of my life, my beloved husband, Prof. Rodwell Kufakunesu, and my cherished children, Gwyneth Mutsa, Takura Nigel, and Chiedza Valerie. Your unwavering support and the countless sacrifices you've made have been the bedrock upon which I built the foundation of this PhD. Your prayers and boundless love have been a steady wellspring of strength, offering solace and encouragement throughout the arduous journey of this pursuit. My dear children, may this thesis stand as a perpetual reminder that the human spirit knows no boundaries, and age is not a constraint when one possesses determination and unwavering resolve. I hope it serves as a testament to the potential within each of you, and that it inspires you to reach for the stars with unwavering belief in your capabilities.

Together, we have weathered the storms and scaled the peaks, and I look forward to many more shared triumphs and moments of joy as we continue this journey of life together.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| ABP | Activation by Personalisation |
| ACK | Acknowledgment |
| ADR | Adaptive Data Rate |
| Bps | Bits per second |
| BW | Bandwidth |
| CCMA | Code Division Multiple Access |
| CF | Carrier Frequency |
| CH | Channel Contention |
| CC | Computational Complexity |
| CR | Code Rate |
| CSS | Chirp Spread Spectrum |
| CV | Coverage |
| DBSK | Differential Phase Shift Keying |
| DL | Downlink |
| DR | Data Rate |
| ED | End Device |
| EE | Energy Efficiency |
| FEC | Forward Error Correction |
| FL-ADR | Fuzzy Logic - Adaptive Data Rate |
| FLS | Fuzzy Logic System |
| F. OMNeT++ | FLoRa OMNeT++ |
| GMSK | Gaussian Minimum Shift Keying |
| GW | Gateway |
| IoT | Internet of Things |
| IP | Internet Protocol |
| ISM | Industrial Scientific and Medical |
| JS | Join Server |
| LoRa | Long Range |
| LoRaWAN | Long Range Wide Area Network |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| LPWAN | Low Power Wide Area Network |
| LTE | Long Term Evolution |
| MAC | Media Access Control |
| NBIoT | Narrowband Internet of Things |
| NS | Network Server |
| OTAA | Over-the-Air-Activation |
| PDR | Packet Delivery Ratio |
| PER | Packet Error Rate |
| PHY | Physical layer |
| PLR | Packet Loss Ratio |
| PSR | Packet Success Ratio |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| QPSK | Quadrature Phase Shift Keying |
| RF | Radio Frequency |
| RSSI | Received Signal Strength Indicator |
| RW | Receive Window |
| SF | Spreading Factor |
| SINR | Signal-to-Interference-to-Noise Ratio |
| SNR | Signal-to-Noise Ratio |
| TB | Testbed |
| TDC | Transmission Duty Cycle |
| ToA | Time-on-Air |
| TP | Transmit Power |
| UL | Uplink |
| UL-PDR | Uplink Packet Delivery Ratio |
| WSN | Wireless Sensor Network |

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# CHAPTER 1 INTRODUCTION

The Internet of Things (IoT) has witnessed tremendous growth in recent years, with organisations across various industries leveraging its capabilities to enhance operational efficiency, improve customer service, and drive business value. In the context of IoT, a "thing" refers to any physical object that is connected to the internet and has the ability to collect, send, or receive data. It is a generic and inclusive term used to encompass the wide range of interconnected devices in the IoT ecosystem. According to [1] there was an 18% increase in global IoT connections in 2022, resulting in 14.3 billion active IoT device connections. Looking ahead to 2023, they predict a further 16% growth, reaching 16.7 billion active devices worldwide. With the proliferation of connected devices, there is a growing demand for robust and efficient communication technologies to maintain the vast ecosystem of IoT applications. In this context, Low-Power Wide-Area Network (LPWAN) technologies have developed as an expedient solution, offering long-range, low-power, and cost-effective connectivity for IoT deployments that need to transmit data infrequently [2]. LPWAN technologies have developed in both licensed and unlicensed markets including Long-Term Evolution for Machines (LTE-M), SigFox, Long-Range Wide Area Network (LoRaWAN), and Narrowband IoT (NBIoT) [3–5].

Amongst the LPWAN systems available, LoRaWAN [6] has garnered significant attention and adoption in IoT applications due to its unique features and benefits. LoRaWAN provides an ideal communication infrastructure for a wide array of use cases, including smart city deployments, precision agriculture, smart healthcare, asset tracking, and industrial monitoring [7–10]. LoRaWAN's low bandwidth and long-range communication capabilities enable end devices (EDs) to transmit data over distances of up to tens of kilometres in rural areas and several kilometres in urban environments, overcoming the limitations of traditional short-range wireless technologies [11]. Furthermore, LoRaWAN's low power consumption is a key advantage in IoT deployments where EDs are often battery-powered and expected to operate for extended periods without frequent maintenance or battery replacements. By minimising power consumption during transmission and standby modes, LoRaWAN enables devices to achieve long battery life, ensuring continuous and reliable connectivity in remote or inaccessible locations [12].

Scalability is another key aspect of LoRaWAN that makes it well-suited for large-scale IoT deployments. The network architecture of LoRaWAN allows for seamless integration of a substantial number of devices, accommodating thousands or even millions of devices concurrently linked to the network. This scalability, coupled with its cost-effectiveness as an unlicensed spectrum technology, significantly reduces deployment and operational costs associated with IoT projects [13]. LoRaWAN also offers flexibility and adaptability to diverse IoT use cases. Its open standard nature fosters interoperability among different vendors and ensures compatibility across devices and networks, allowing for seamless integration within IoT ecosystems. This versatility enables the implementation of LoRaWAN in various environments, both indoor and outdoor, making it a versatile choice for a broad array of IoT applications [14]. Furthermore, security is a crucial concern in the IoT landscape, and LoRaWAN addresses this with robust security features. It incorporates encryption and authentication mechanisms to ensure secure data transmission and protection against unauthorised access or tampering, safeguarding sensitive data in applications such as healthcare, industrial monitoring, and smart infrastructure.

## 1.1 PROBLEM STATEMENT

LoRaWAN devices typically have small batteries, which can limit their lifetime. There needs to be ways to enhance the energy efficiency of LoRaWAN networks to extend the network life of the end nodes. The Adaptive Data Rate (ADR) scheme is one such method. The objective of this scheme is to minimise energy consumption and maximise throughput by adjusting the data rate dependent on the link budget for every end node in a LoRaWAN. ADR controls the transmission parameters, namely Bandwidth (BW), Spreading Factor (SF), Transmission Power (TP) and Coding Rate (CR). Appropriate resource allocation of the transmission parameters is required to optimise data rates, energy utilisation, scalability and network performance. Numerous adaptive data rate algorithms that have been developed seek to solve the challenges of scalability [15–17], congestion [18–20], throughput [21–23] and packet delivery ratio [24, 25]without focusing on the schemes' impact on energy consumption. The most ubiquitous challenge that exists regarding LoRaWAN deployments is energy efficiency.

### 1.1.1 Context of the problem

In LoRa implementations found in literature, ADR schemes are implemented and evaluated using different approaches such as mathematical models, simulations, and testbeds. Despite the growing adoption of LoRaWAN in IoT applications and its numerous benefits, the implementation and optimisation of the Adaptive Data Rate scheme within LoRaWAN networks present significant challenges. The lack of standardised guidelines for ADR implementation has resulted in diverse proprietary approaches from different vendors, leading to a fragmented landscape of ADR schemes. This diversity creates difficulties in ensuring reliability, performance, and suitability. Given the significance and unique capabilities of LoRaWAN in IoT applications, there is a growing need for in-depth research and analysis to further enhance its performance and optimise its utilisation of ADR for specific IoT deployments with varying quality of service (QoS) requirements.

The ADR algorithm is implemented in the LoRaWAN network to independently regulate the TP and data rate for all the EDs. LoRaWAN network performance is directly affected by the power consumption in the EDs since the end devices have limited battery capacity. Because of the LoRaWAN Regional Parameters and Specifications [6, 26] EDs must cater for specific data rates, further compounding the power constraint predicament since the signal-to-noise ration (SNR) values must cross certain thresholds and power levels. Because the EDs must respond to the channel conditions in the network, it implies they must be able to control the data rates and transmission power accordingly [27].

### 1.1.2 Research gap

Following the introduction of the LoRaWAN protocol in 2015, scholarly investigations have primarily concentrated on the improvement of network performance of the LoRaWAN network using the Adaptive Data Rate algorithm. Resource allocation is the mechanism by which coverage, time-on-air and interference can be improved. Numerous surveys have been conducted on the resource allocation in LoRaWAN using the ADR scheme [14, 28–30]. The initial ADR schemes [31–34] were primarily developed to address the issues of scalability, congestion, throughput and packet delivery ratio. However, these algorithms did not prioritise the examination of their impact on energy consumption. In literature, a few studies consider the issue of energy consumption in relation to improving network performance. The existing solutions that have been proposed do not exploit fully the energy efficiency of the ADR algorithms. While some address issues like collision probability and packet delivery, they often do so at the expense of other factors that impact energy use. For example, some approaches optimize for overall network performance but don’t consider the specific needs of different types of devices or the presence of multiple gateways. Furthermore, some approaches assume simplified network conditions, such as a fixed number of devices or a uniform distribution, which may not reflect real-world scenarios. Overall, there's a need for optimization strategies that take a more holistic view of the network and consider the energy consumption of individual devices as well as other performance metrics. Given the significance and unique capabilities of LoRaWAN in IoT applications, there is a growing need for in-depth research and analysis to further enhance its performance and optimise its energy utilisation. This research gap needs to be addressed to resolve specific challenges related to LoRaWAN's ADR scheme, which plays a pivotal maximising network performance on the energy-constrained EDs. By evaluating existing ADR schemes and proposing an improved energy-efficient ADR scheme, this research contributes to the advancement of LoRaWAN technology, enabling more efficient and scalable IoT applications.

## 1.2 RESEARCH OBJECTIVE AND QUESTIONS

The primary objective of this research study is to enhance the performance of LoRaWAN networks, specifically focusing on the Adaptive Data Rate scheme by reducing energy consumption to extend the battery life of static end devices. By investigating the underlying causes of energy wastage, novel techniques for improving energy efficiency will be devised. Additionally, the research will explore strategies for managing resource allocation effectively within the ADR scheme while maintaining optimal energy consumption levels, thereby optimising network performance, and prolonging the battery life. The research questions this thesis attempts to answer are as follows:

- What is the impact of optimising ADR schemes on network performance in a LoRaWAN environment?
- How can energy consumption in a LoRaWAN ADR scheme be effectively managed and enhanced to achieve higher efficiency?
- What interference avoidance ADR scheme can be implemented to enhance the packet delivery ratio of a LoRaWAN network while ensuring minimal impact on energy consumption?
- What specific performance metrics can be employed to assess and validate the efficacy of the developed ADR algorithm?

## 1.3 THESIS STATEMENT AND APPROACH

The implementation of Adaptive Data Rate optimisation techniques in LoRaWAN networks enhances network performance by reducing energy consumption, leading to notable improvements in energy efficiency.

The research study adhered to the well-established protocol for conducting technical research in the domain of engineering, with a specific focus on electronic and computer engineering. The following steps of this research project's execution are highlighted:

- **Literature review**: During the initial phase of this research study, a comprehensive analysis of LoRaWAN was conducted, specifically emphasising the Adaptive Data Rate Algorithm and the associated challenges it presents.
- **System Modelling and Simulation**: A novel energy-efficient adaptive data rate algorithm was developed and evaluated, taking into account the identified gaps. An ADR algorithm that improves packet delivery ratio by reducing packet collision and managing interference was also developed. Subsequently, a search was carried out to determine a suitable simulator for the implementation, monitoring and analysis of the ADR schemes and the network performance.
- **Performance Evaluation**: In the final phase, the designed system models were simulated in the ns-3 environment and their performance was compared with existing ADR algorithms. The obtained results are systematically presented and discussed in the various chapters of this thesis, providing comprehensive insights and discussions.

## 1.4 RESEARCH GOALS

The principal goal of this research was to develop a novel adaptive data rate algorithm for the purpose of enhancing energy efficiency within the LoRaWAN network, with a particular emphasis on confirmed traffic. The supplementary goal was to investigate and develop an algorithm that improved the packet delivery ratio with minimal impact on energy consumption.

## 1.5 RESEARCH CONTRIBUTION

This research study contributed to the existing body of knowledge on LoRaWAN networks and Adaptive Data Rate Algorithms as follows:

- A comprehensive review of the implementation of the adaptive data rate schemes in LoRaWAN was conducted. The review provides a complete scope of the strengths and drawbacks of existing ADR schemes and the solutions they provide, classified according to objectives, the optimisation approach, the metrics used and the computational complexity involved.
- A comprehensive study of the impact of gateway and end device density on the performance of LoRaWAN was investigated to determine the optimal number of gateways that can be used in a LoRaWAN network to maximise scalability and its effect on energy consumption.

- An in-depth investigation of the effect of different signal-to-noise ratio history averaging methods used in ADR algorithm implementation on the performance of LoRaWAN networks. The study provides an understanding of how the ADR algorithm optimises the network performance.
- The design and development of a novel fuzzy-logic-based ADR algorithm that improves energy efficiency in LoRaWAN.
- The design and development of a stochastic probability model for optimising the ADR algorithm to increase packet delivery ratio without compromising energy utilisation.

## 1.6 RESEARCH OUTPUTS

The findings of this research study have been published or are currently under review in peer-reviewed journals and conferences. The following is a compilation of the research outputs:

### 1.6.1 Journal articles

- R. Kufakunesu, G. P. Hancke, and A. M. Abu-Mahfouz, "A Survey on Adaptive Data Rate Optimization in LoRaWAN: Recent Solutions and Major Challenges," *Sensors*, vol. 20, no. 18, p. 5044, 2020.
- R. Kufakunesu, G. P. Hancke, and A. Abu-Mahfouz, "A Fuzzy-Logic Based Adaptive Data Rate Scheme for Energy-Efficient LoRaWAN Communication," *Journal of Sensor and Actuator Networks*, vol. 11, no. 4, p. 65, October 2022.
- R. Kufakunesu, G. P. Hancke, and A. M. Abu-Mahfouz, "Collision Avoidance Adaptive Data Rate Algorithm for LoRaWAN," *Computer Networks*, (under review).

### 1.6.2 Conference articles

- R. Kufakunesu, G. P. Hancke, and A. M. Abu-Mahfouz, "Towards Achieving an Efficient ADR Scheme for LoRaWAN: A Review of the Constrained Optimisation Approach," in *Southern Africa Telecommunication Networks and Applications (SATNAC)*. Telkom, 2021, pp. 2-7.
- R. Kufakunesu, G. P. Hancke, and A. M. Abu-Mahfouz, " The Impact of Gateway Node Density on the Performance of LoRaWAN," In *Proceedings of the Southern Africa Telecommunication Networks and Applications Conference (SATNAC)*. Telkom, 2022, pp. 214-217.
- R. Kufakunesu, G. P. Hancke, and A. M. Abu-Mahfouz, "Evaluating the Impact of the Adaptive Data Rate Algorithm in LoRaWAN," in *Southern Africa Telecommunication Networks and Applications Conference (SATNAC)*. Telkom, 2023, pp. 274-278.

## 1.7 DELINIATION AND LIMITATIONS

The research study faced a challenge due to the unavailability of LoRaWAN testbeds for the implementation and evaluation of the developed Adaptive Data Rate algorithms. Establishing a LoRaWAN testbed with a sufficient number of end devices would have incurred substantial expenses and necessitated continuous maintenance. Consequently, this research work was carried out leveraging the ns-3 simulation software as a suitable alternative. Although the use of simulation software offers cost-effectiveness, flexibility, scalability, reproducibility and repeatability, among other benefits, it is a representation of the real world and results may not always perfectly mirror real-world deployments due to simplifications and assumptions made in the simulation models. The research study uses the Europe regional specifications (EU-868MHz) for LoRaWAN and Class A EDs using confirmed traffic. The word end device is used interchangeably with the word end node in this thesis. The path loss model utilised in this research does not account for the effects induced by streets and buildings. The employed LoRaWAN network was predicated on the assumption of operating as a standalone network, thereby excluding potential interference from other LoRaWAN networks or coexisting transmissions within the same frequency bands. Therefore, it is imperative to regard the results presented as a fundamental reference point, subject to potential variations in real-world implementations.

## 1.8 OVERVIEW OF STUDY

In Chapter 2, the background knowledge of LoRaWAN and a review of relevant literature on adaptive data rate algorithms are presented. The primary objective of this chapter is to analyse the current literature relating to LoRaWAN and ADR schemes to identify research gaps. In Chapter 3 a novel fuzzy logic-based ADR (FL-ADR) algorithm is proposed to improve performance in terms of energy efficiency, packet success rate and interference rate, including the system model, simulation setup and implementation. The numerical and simulation results and the discussion of the proposed algorithm are also presented. In Chapter 4, an SNR-based Spreading Factor Interference Rate controlled Adaptive Data Rate Algorithm, SSFIR-ADR, that improves packet delivery ratio by reducing packet collision and managing interference is introduced, followed by the performance evaluation and results discussion. Chapter 5 concludes the thesis and presents research opportunities for future work.

# CHAPTER 2 LITERATURE STUDY

## 2.1 CHAPTER OVERVIEW

The Internet of Things (IoT) refers to a vast interconnected network comprising various physical end devices and objects that have connectivity capabilities and are equipped with sensors and the requisite software. These facilitate the seamless gathering and exchanging of data over the internet. These devices, often referred to as "smart" devices, can establish communication and interaction among themselves and with people, thereby establishing a connected ecosystem. In numerous industries, organisations are progressively adopting the IoT as a means to enhance operational efficiency, gain deeper insights into customer behaviour, deliver enhanced customer service, facilitate informed decision-making, and augment overall business value. Consequently, there has been a significant increase in the quantity of internet-connected devices. In the realm of the Internet of Things, various entities can be classified as "things." An example of one of these entities is a person who has had a medical procedure that involves implanting a heart monitoring device. Other examples include homes with intelligent systems that control the heating and lighting on their own, animals with biochip transponders that allow for tracking, cities that have been designed to be smart, and factories that use monitoring systems to find and fix problems with their machinery before they break down. These devices must possess the capability to obtain an Internet Protocol (IP) address and the capacity to transmit data across a network. LoRaWAN is a fast-growing communication system for Low Power Wide Area Networks in the Internet of Things deployments. LoRaWAN is built to optimise LPWANs for battery lifetime, capacity, range, and cost and employs an ADR scheme that dynamically optimises data rate, airtime, and energy consumption in a resource-constrained network. This chapter provides a comprehensive examination of the LoRaWAN protocol, focusing on an exploration of ADR schemes documented in the existing literature. The study investigates the solutions proposed for optimising ADR in LoRaWAN networks, as well as identifies and discusses the significant challenges that persist in this domain. The findings discussed in this chapter are based on the scholarly publication entitled "A

Survey on Adaptive Data Rate Optimisation in LoRaWAN: Recent Solutions and Major Challenges" [29], which delves into the fundamental concept of ADR within LoRaWAN networks.

This chapter is structured as follows: Section 2.2 introduces the Internet of Things focusing on LPWANs. Section 2.3 presents an overview of the LoRaWAN technology. Section 2.4 focuses on the adaptive data rate mechanism of LoRaWAN. Section 2.5 presents the different ADR schemes developed to enhance LoRaWAN performance. Section 2.6 provides a comparison and discussion of the ADR Schemes and their classification. Section 2.7 focuses on the challenges presented by the ADR schemes and the way forward in solving the challenges. Finally, Section 2.8 provides a summary of the chapter.

## 2.2 INTERNET OF THINGS

The Internet of Things is made possible through the integration of several key technologies. IoT relies on sensors to detect changes in the environment, like temperature, humidity, light, motion, or pressure. Actuators, on the other hand, enable physical changes in the environment, such as opening a valve or activating a motor. These devices form the core of IoT, allowing machines and devices to interact with the physical world and enabling automation without human intervention. For IoT devices to transmit data to the cloud, they require internet connectivity. Various technologies like Wi-Fi, Bluetooth, cellular, Zigbee, and LPWANs are used to establish these connections. The vast amounts of data generated by IoT devices are stored, processed, and analysed in the cloud. Cloud computing platforms provide the necessary infrastructure and tools for data storage, analysis, and the development of IoT applications. Extracting meaningful insights from the massive volumes of data generated by IoT devices requires advanced analytics tools. Machine learning algorithms, data visualisation tools, and predictive analytics models are employed to make sense of this data. As IoT becomes more widespread, ensuring the security and privacy of IoT devices and the data they generate becomes important. Technologies such as encryption, access controls, and intrusion detection systems are employed to protect against cyber threats. Network and cyber security are beyond the scope of this work.

The evolution of IoT can be attributed to technological advancements, making it highly relevant across diverse industries. The emergence of the Internet of Things can be attributed to the late 1990s and early 2000s, a time when the widespread adoption of technologies such as Radio Frequency Identification (RFID) and wireless sensor networks (WSN) occurred. These advancements facilitated the connection of physical objects to the internet, giving rise to the concept of IoT [35]. These technologies enabled the identification, tracking, and monitoring of objects and assets. Connectivity stands as a pivotal aspect of IoT, with the availability of affordable and extensive wired and wireless internet connectivity aiding in its growth. Furthermore, the miniaturisation and cost reduction of sensors and embedded systems have facilitated the integration of devices with a wide range of sensing capabilities, encompassing temperature, humidity, motion, and more [36].

To facilitate these advancements, Low-Power Wide-Area Network (LPWAN) technologies like LoRaWAN, Sigfox, and NBIoT have been deployed. These technologies provide efficient, low-power connectivity for IoT devices over long distances. They enable reliable data transmission and facilitate the seamless integration of IoT devices into existing networks. These technologies possess distinct advantages and disadvantages, and the selection process is contingent upon particular criteria such as range, data rate, power consumption, scalability, and cost. Overall, LPWAN technologies have significantly contributed to the growth and effectiveness of IoT deployments, empowering organisations and industries to harness the full potential of IoT data for enhanced decision-making and operational efficiency.

### 2.2.1 Long Range Wide Area Networks

LoRaWAN has a larger ecosystem and a vibrant community of developers and solution providers, offering a wider range of compatible devices, gateways, and tools. This can provide more options and support when building and deploying LoRaWAN-based IoT solutions. LoRaWAN networks are highly scalable and capable of accommodating a significant number of devices, making them suitable for massive IoT deployments. LoRaWAN also allows for private network deployments, providing flexibility for organisations that want to have full control over their IoT infrastructure. LoRaWAN supports higher data rates and larger payload sizes compared to Sigfox. It allows for more flexible data transmission, accommodating applications that require higher bandwidth or larger amounts of data to be transmitted.

### 2.2.2 Sigfox

Sigfox is a cutting-edge cellular wireless communication technology that specialises in providing customised solutions with a primary focus on low-throughput IoT and Machine-to-Machine (M2M) applications. The name Sigfox refers to both the protocol and the PHY, as well as the corporation that owns and operates the network. The Sigfox network protocol incorporates patented base stations equipped with software-defined radios, ensuring efficient and reliable end-to-end communication

[11]. In this architecture, the EDs utilise binary phase-shift keying (BPSK) modulation to establish connectivity with the base station, enabling seamless data transmission and reception. Sigfox operates in the unlicensed sub-gigahertz ISM bands, specifically 868 MHz in Europe and 915 MHz in North America utilising ultra-narrowband (UNB) modulation, which allows for efficient spectrum utilisation and long-range communication of up to 10km in urban settings and up to 50km in rural areas [12]. Sigfox operates at a low data rate, typically around 100 bits per second (bps) with a payload size limited to 12 bytes per message, rendering it appropriate for the transmission of small data quantities, such as sensor readings or status updates.

### 2.2.3 NBIoT

Narrowband Internet of Things (NBIoT), also referred to as LTE Cat-NB1, is a standardised cellular network technology developed specifically to provide for the specific requirements of IoT applications that prioritise extended battery life, wide coverage, and minimal data rates. The initiative for NBIoT was undertaken by the Third-Generation Partnership Project (3GPP) within the GSM/EDGE Radio Access Network (GERAN) domain, initially aimed at repurposing the 200 KHz GSM spectrum for IoT deployments. Subsequently, the project expanded to encompass 3GPP RAN, enabling support for LTE in-band, guard-band, and standalone installations. The 3GPP NBIoT work item was successfully finalised in June 2016 [37]. NBIoT networks offer extensive coverage, facilitating communication even in remote or underground regions where traditional cellular networks exhibit limited connectivity. Leveraging licensed spectrum via existing cellular infrastructure, NBIoT can coexist harmoniously with other cellular technologies like 2G, 3G, and 4G LTE, without causing interference. This seamless integration enables smooth integration and migration of IoT devices into established network infrastructures. NBIoT's operational characteristics allow it to function effectively within narrow bandwidths, resulting in reduced network deployment and operational costs. Security is a paramount concern for NBIoT, and it employs robust mechanisms to safeguard the confidentiality and integrity of data transmitted between devices and the system. These measures effectively prevent unauthorised access or tampering [38].

### 2.2.4 Weightless

Weightless is an LPWAN wireless technology that was introduced by the Weightless Special Interest Group (SIG). The technology encompasses a trio of open LPWAN standards, specifically termed Weightless-W, Weightless-N, and Weightless-P. These standards have been engineered to function in both the unlicensed and licensed spectrum, catering to various ranges and ensuring minimal power utilisation. This technology leverages cognitive radio and TV white spaces to allow EDs to opportunistically utilise these frequency bands without causing interference to the principal devices, which are owned by licensed operators [39]. Weightless-N in a UNB standard that uses Differential Phase-Shift Keying (DBSK) modulation to provide a unidirectional transmission from the ED to the base station. The technology utilises TV white space frequencies within the range of 470–790 MHz. Weightless-N supports data rates that range from a few kilobits per second up to tens of kilobits per second. Weightless-P is a narrowband LPWAN technology with bi-directional communication using Gaussian Minimum Shift Keying (GMSK) and Quadrature Phase Shift Keying (QPSK) modulation. It provides higher data rates compared to Weightless-N, rendering it well-suited for applications that necessitate more frequent and larger data transmissions. Weightless-P is designed to support data rates up to several megabits per second. Weightless-W is a standard supporting DBSK and 16-Quadrature Amplitude Modulation (16-QAM) which supports data rates up to 10mbps depending on the link budget.

### 2.2.5 Ingenu RPMA

Ingenu designed and built Random Phase Multiple Access (RPMA) for IoT and M2M applications. This LPWAN system utilises the unlicensed spectrum, globally available on the 2.4 GHz ISM band. The fundamental basis of Ingenu's wireless technology is the implementation of RPMA [40] utilising Direct Sequence Spread Spectrum (DSSS) facilitating uplink communication. This approach permits the concurrent utilisation of a single time slot by multiple transmitters as a viable alternative to Code Division Multiple Access (CDMA). By introducing a randomised backoff interval for every transmitter within the designated time slot, the overlap between transmitters is reduced, thereby enhancing the signal-to-interference ratio for individual links [41]. Ingenu RPMA also facilitates bi-directional transmission capabilities. In the case of downlink communication, base stations continually broadcast signals to end devices that are individually connected, employing CDMA for broadcasting. Moreover, Ingenu RPMA adheres to established IEEE 802.15.4k requirements, ensuring compatibility with existing infrastructure and devices compliant with this standard. This compatibility feature allows for seamless integration with the broader ecosystem of devices and networks that operate based on the IEEE 802.15.4k standard.

### 2.2.6 LTE-M

Long-Term Evolution for Machines (LTE-M), alternatively termed Cat-M, released by 3GPP in 2016, is a LPWA communication technology designed specifically to provide for the distinct requirements of IoT devices. It is a variation of the 4G LTE network technology and is optimised for low power, low cost, and extended coverage for IoT applications. It is a narrow-bandwidth cellular communications standard used to link resource-constrained devices to the Internet that transfer modest quantities of data over long periods of time while maintaining strong signal penetration and low power consumption. LTE-M provides better coverage compared to traditional cellular networks. It can penetrate buildings and underground areas more effectively, enabling reliable connectivity for IoT devices in various environments. It uses narrowband technology, which requires less bandwidth and infrastructure investment compared to traditional cellular networks.

**Table 2.1.** Comparison of IoT Technologies

| **Technology** | **Advantages** | **Disadvantages** |
|---|---|---|
| LoRaWAN | - Low deployment cost<br>- Decentralized architecture<br>- Good security<br>- Excellent scalability<br>- Allows private network deployments<br>- Vibrant developer community<br>- Flexible data rat<br>- Large ecosystem of devices and gateways | - Limited bandwidth<br>- Complex network setup for private deployments<br>- Susceptible to interference in dense areas |
| SigFox | - Low power consumption<br>- Wide coverage area<br>- Simple network architecture<br>- Cost-effective<br>- Cellular wireless communication | - Limited data rate<br>- Limited scalability<br>- Patented base stations<br>- Limited number of messages per day<br>- Limited payload size<br>- Less robust security |
| NBIoT | - Robust security<br>- Uses existing cellular infrastructure | - Licensed spectrum |
| Weightless | - Operates under licensed and unlicensed spectrum<br>- Uses cognitive radio and TV whitespace | - Limited Adoption<br>- Less mature technology |
| Ingenu RPMA | Unlicensed spectrum<br>- Bidirectional transmission<br>- Compatible with existing infrastructure | -Proprietary network<br>- Limited device selection<br>higher cost compared |
| LTE-M | Strong signal penetration<br>- Uses less bandwidth | -Draconian licensing issues<br>- Limited coverage worldwide |

## 2.3 LONG RANGE WIDE AREA NETWORKS

LoRaWAN protocol was first released in 2015 by the LoRa Alliance. The LoRaWAN functions in an unlicensed sub-gigahertz industrial, scientific and medical (ISM) band (863–870MHz band in Europe and 902–928MHz in the USA). It uses the 125KHz, 250KHz and 500KHz bandwidth and transmits payloads of up to 250 Bytes over 5-20km. The system consumes low power and can last up to five to ten years of battery life [6, 42]. LoRa represents "Long Range", a long-range wireless communications technology, endorsed by the LoRa Alliance. The main objective of this technology is to be functional in long-lasting battery-operated end nodes, where energy efficiency is of utmost priority. LoRa consists of two distinct layers, namely a physical layer that uses the Chirp Spread Spectrum (CSS) radio modulation system and a MAC layer protocol known as LoRaWAN. However, the LoRa communication system furthermore denotes a particular access network architecture [43]. LoRaWAN is constructed to optimise deployment cost, capacity, range, and battery lifetime in LPWANs. LoRa, the physical layer or modulation employed to generate the long-range wireless connection, provides multiple transmission parameters. These parameters are BW, SF, TP and CR. Varying these parameters affects network performance.

Towards the end of 2018, a LoRa-based solution was introduced, offering the potential for increased bandwidths and data rates in the 2.4GHz ISM-band. In addition, it surpasses the restricted duty-cycle imposed by regulations in the ISM-bands, allowing for the exploration of numerous innovative application areas. In addition, the increased bandwidth and faster transmission times make the exploration of alternative MAC layer protocols quite intriguing. For instance, TDMA-based approaches offer promising possibilities [44, 45]. Unlike the sub-GHz band, LoRa 2.4 GHz does not have duty-cycle limitations. For example, in Europe, regional regulations impose a 1% duty-cycle limitation. However, with LoRa 2.4 GHz, devices can send data at any time or, ideally, when the medium is free. In an area where a channel is not being utilized, a device can fully utilize a LoRa 2.4 GHz network [46]. The work in [47] presents a mathematical description of the physical layer of LoRa in the 2.4 GHz band. They examine the maximum communication range of this technology in three distinct scenarios. Simulation of signal propagation at various spreading factors and bandwidths involves the utilization of free space, indoor, and urban path loss models. These models help analyze the behaviour of the 2.4 GHz LoRa modulated signal. Additionally, they analysed the data rates relevant to the situation. Based on the data, it is evident that the range varies depending on the environment. In free space, the maximum range achieved is 133 km, while in an indoor office-like environment, it drops to 74 m. However, in an outdoor urban context, the range increases significantly to 443 m.

The LoRa network comprises five main components: the end nodes also known as end devices, the gateway, the NS, the Join Server (JS) and application servers connected in a star topology architecture. The LoRa end node contains a wireless transceiver and sensor nodes that transmit data to multiple gateways in its vicinity using LoRa radio frequency (RF) Modulation. Gateways are powered by the mains and have internet connectivity. They consist of a radio component with a transmitter and a microprocessor for data processing. Every gateway in the network sends the received data packet to the cloud-based NS which successively directs the packet to the appropriate application server. If a network has multiple gateways, it is possible for all the gateways to receive data from the same end node. Gateways can concurrently listen to several frequencies in every SF. Figure 2.1 shows the LoRaWAN architecture.

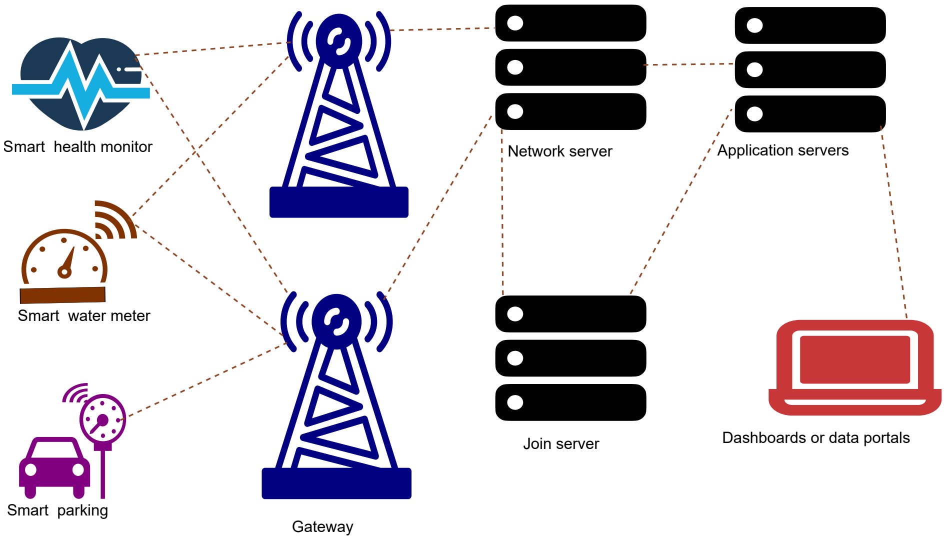


**Figure 2.1.** LoRaWAN architecture. Adapted from [43], (c)2015, Semtech.

When an end node forwards a data packet to the gateway, it is known as an uplink (UL) and when the gateway forwards a data packet to the end node, it is called a downlink (DL). End nodes broadcast their data packets to every gateway in the vicinity and the gateways transmit the data to the NS. The NS sends the data package to the correct application server, where the end-user can process the data. The NS receives the response from the application server and establishes which gateway will send the message back to the end nodes. Two types of messages can be transmitted at any given time in any LoRaWAN operation. These are unconfirmed messages, where the end nodes do not request a response from the NS and confirmed messages that request a response. For the end nodes to be deemed active entities, they are required to first connect to the network and be allocated a series of parameters that are essential for operation in a LoRaWAN through the JS. The LoRaWAN network contains two major security elements, the join procedure and message authentication. This guarantees that only authentic and certified end nodes are joined to authentic and bona fide networks. The implementation of end-to-end encryption for application payloads that are exchanged between the end nodes and the application servers is also provided by LoRaWAN as a security measure.

LoRaWAN is among a small number of IoT systems that implement end-to-end encryption. The JS is responsible for secure device activation and key storage and management. It indicates to the NS which application server should be connected to the end nodes and executes the encryption key derivations for the network and application session. The network session key of the end node is communicated to the NS, and the application session key to the corresponding application server. LoRaWAN permits two kinds of end device activation, namely, Over-the-Air Activation (OTAA) and Activation by Personalisation (ABP). The OTAA process permits end nodes to validate and secure access to the network with security credentials. ABP is a simpler and less secure process which skips the join procedure. The LoRaWAN protocol does not support direct communication between end nodes [43]. Security is a huge challenge in IoT networks. The authors in [48] provided an extensive Security Risk Analysis of the LoRaWAN v1.1 protocol and discussed numerous countermeasures to the security risks outlined. They presented a “threat” catalogue, as well as propositions and analyses regarding the magnitude, effect, and possibility of each threat. Other suggestions for improving the network security have been suggested in [49–51].

### 2.3.1 LoRaWAN protocol

The LoRaWAN protocol is a comprehensive framework consisting of a well-defined set of specifications and standards. These guidelines facilitate an implementation that enables seamless integration of LoRaWAN devices into IoT applications and streamlines the deployment and management of LoRaWAN networks. These specifications are developed and maintained by the LoRa Alliance, an open, non-profit organisation of businesses that collaborate to drive the adoption and interoperability of LoRaWAN technology. The protocol specifies the technical implementation but does not specify any commercial model or deployment type, thereby allowing the industry the autonomy to foster innovation and establish distinct approaches to its utilisation. The LoRaWAN specifications are continuously evolving as the technology advances, and new versions and updates may be released by the LoRa Alliance to address emerging requirements and enhance the capabilities of LoRaWAN networks.

The LoRaWAN protocol serves as the foundation for configuring modulation parameters within the LoRa protocol and defining the frequency channels to be employed, taking into account the specific geographical region of deployment, such as Europe, North America, Asia, and other regions. Notably, LoRaWAN networks leverage unlicensed frequency bands allocated for ISM purposes, subject to variation according to the localised geographical area. Furthermore, the protocol provides a comprehensive framework for adhering to the local regulations and guidelines governing the utilisation of designated channels. By adhering to these procedures, LoRaWAN networks ensure compliance with pertinent rules, facilitating the seamless and lawful operation of LoRaWAN technology in diverse locations across the globe.

The initial version of the LoRaWAN specification published by the LoRa Alliance in 2015 is LoRaWAN 1.0.0. It defined the basic principles and features of the LoRaWAN protocol, including the MAC layer protocol, security mechanisms, and regional parameters, and introduced Class A devices that support bi-directional communication with low power consumption. In 2017 a significant update was released, version 1.1 which introduced additional MAC commands and added security features and support for roaming devices. Version 1.0.2 was released in 2018 introducing additional features and improvements, including functionality for Class B and Class C devices, allowing more flexible and efficient communication patterns. Class B devices have better scalability compared to Class A devices because they support scheduled receive windows, allowing for more predictable communication [52]. They periodically open receive windows to listen for downlink messages from the network server. This periodic listening enables quicker response times compared to Class A devices. However, the scalability of Class B devices can be limited by the need to synchronize with the network's beacon and scheduled receive windows. Managing a large number of synchronized devices might become challenging in dense deployments [53]. Class C devices offer even higher scalability compared to Class B devices because they keep their receive windows open all the time except when they are transmitting, allowing for nearly instantaneous communication. These devices are ideal for applications requiring real-time downlink communication or where the devices need to be accessible at any time. However, the continuous listening characteristic of Class C devices consumes more power compared to Class A and B, which might be a consideration in battery-powered deployments [54]. Figure 2.2 shows the LoRaWAN device classes. The latest version 1.0.4 published in October 2020 made refinements to the coexistence of device classes, ADR management and security issues.

The LoRaWAN specification defines the regional parameters for LoRaWAN networks, including frequency bands, channel plans, data rates, and other region-specific settings. It ensures that LoRaWAN

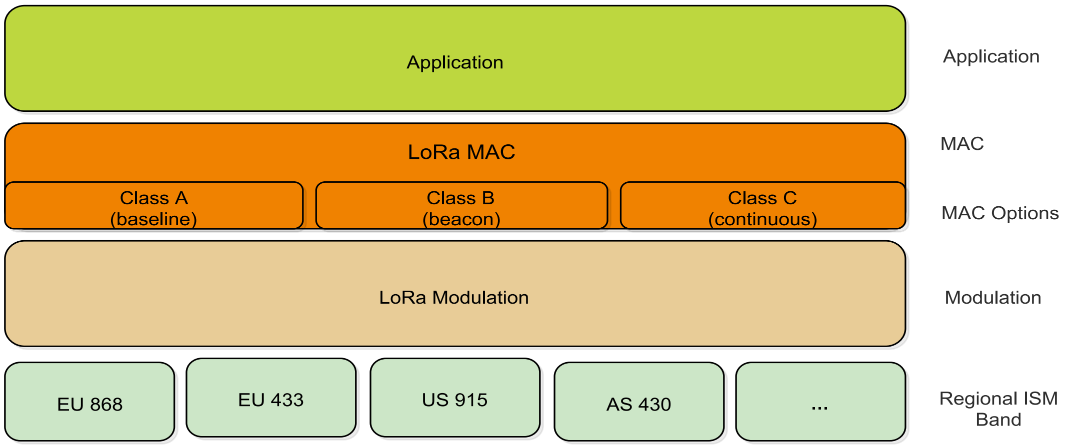


**Figure 2.2.** LoRaWAN device classes. Adapted from [6], (c)2018, Semtech.

networks can operate within the regulatory requirements of different countries or regions (EU868, EU433, US915, AS430). In this research study, the European regional parameters EU868 are considered. The MAC layer specification defines the communication protocol for LoRaWAN devices and gateways. It includes rules for channel access, frame structure, data rate adaptation, acknowledgement mechanisms, and security procedures. The Backend Interfaces specification describes the interfaces and protocols used for transmission between LoRaWAN end nodes, gateways, and network servers. It defines the messages, formats, and procedures for device activation, data transmission, and network management. The security specification outlines the security mechanisms and procedures ensuring the integrity, confidentiality, and authenticity of data conveyed across LoRaWAN networks. It includes encryption, message integrity checks, and device authentication procedures. Finally, the application layer specification provides guidelines for the application-level communication between devices and application servers. It defines the application data format, messaging formats, and application interfaces.

### 2.3.2 LoRa

LoRa is the physical (PHY) layer of the LoRa technology, which utilises Chirp Spread Spectrum modulation and Forward Error Correction (FEC) that trades off data rate for sensitivity within a fixed BW. This combination enables long transmission ranges with low power characteristics as the chirp signals use the available bandwidth immediately. This characteristic makes the chirp signals robust from interference and noise. Each LoRa packet consists of a preamble of 10 chirps and 6 synchronisation chirps followed by the data. Multiple data bits (chips) can be modulated by one chirp. The SF parameter determines the number of bits that are modulated. For instance, SF7 means a chirp can be encoded with seven bits. Transmitting a data packet with a higher SF implies additional bits are encoded into the chirp, resulting in additional Time on Air (ToA) and a reduced data rate, although it enhances robustness to noise. Three other parameters are involved in LoRa modulation that is BW, TP, and CR. Three bandwidth settings are available namely 125KHz, 250KHz and 500KHz. There are four different code rate options available: 4/5, 4/6, 4/7 and 4/8 [55]. These parameters collectively determine the data rate, which is also termed the LoRa modulation bit rate $R_b$. The correlation between data transmission rate and CR, BW, and SF is expressed in Equation (2.1) [56].

$$R_b = SF * \frac{BW}{2^{SF}} * CR, \tag{2.1}$$

where $SF$ is spreading factor, $BW$ is modulation bandwidth and $CR$ is code rate.

Tuning the parameters above results in a number of the end-to-end transmission characteristics such as data rate, error correction capacity and communication range to be variable [13]. Although a combination of SF, BW and CR is possible theoretically, practically SF and BW are combined to form the data rate, depending on the LoRaWAN regional parameters specification [26]. The specification document specifies the different regulatory requirements of LoRaWAN depending on the location of the deployment. In North America, for instance, there are 64, 125 kHz LoRa UL channels that have been specified, centred on a 200 kHz raster. Eight 500 kHz UL channels as well as eight, 500 kHz DL channels have also been specified. The gateways have the capacity of up to 64, 125 kHz UL channels and eight 500 kHz UL and DL channels. In Europe, LoRaWAN defined ten channels, eight of which have multiple data rates from 250bps to 5.5 kbps. The specification also has one high data rate LoRa channel at 11kbps, and one frequency shift keying (FSK) channel at 50kbps.

The European Telecommunications Standards Institute (ETSI) allows maximum output power in Europe at +14dBM, except the G3 band which allows +27dBm. Duty cycle restrictions exist under ETSI but there are no limitations on maximum transmission or ToA. As an example, the regional settings EU863-870 used in Europe and US902-928 used in North America have data rates ranging from SF7BW125 to SF12BW125 and SF7BW125 to SF10BW125, respectively. The ADR adjusts the data rate depending on the available link budget. The larger the SF applied, the further the signal travels and the less the interference at the receiver. With the bandwidth fixed at BW125 as given in the example, lowering the SF increases the data rate, thereby minimising the ToA for data packets making the gateway more sensitive to noise. The end nodes that are nearest to a gateway transmit using the lowest SF thereby prolonging the battery life because of the effect of ToA. More distant sensors transmit at a higher SF but the data rate will be low. A compromise is made between battery power and range considering that a higher SF allows for gateways to connect to end nodes further away due to higher reception sensitivity. Table 2.2 provides the characteristics of the LoRaWAN technology.

**Table 2.2.** Characteristics of LoRaWAN [6].

| Characteristic | Description |
|---|---|
| Modulation | CSS |
| Frequency | Sub-GHz ISM: EU868, EU430, US918, AS433 |
| Bandwidth | 125kHz and 250kHz |
| Data rate | 0.3 – 5Kbps |
| Range | 5km (urban), 20km (rural) |
| Maximum payload | 250bytes |
| Error correction | FEC |
| Data transmission | Half-duplex |
| Topology | Star |
| Standardization | LoRa-Alliance |

### 2.3.3 LoRaWAN MAC

The LoRaWAN MAC protocol represents an open-source, standardised protocol, established by the LoRa Alliance, functioning at a layer above the LoRa physical layer. Operating within this framework, the LoRaWAN MAC layer defines the essential MAC control process, enabling seamless data transmission between numerous end nodes and gateways. Within this context, the MAC protocol assumes the critical responsibility of equipping LoRa end nodes with fundamental services like channel access, adaptive data rate management, security features, and energy-saving mechanisms [57]. The deployment of thousands of end nodes requires extensive access to improve simultaneous transmissions and circumvent packet collisions. The LoRaWAN MAC uses Aloha to coordinate the links, dividing airtime among end nodes to handle packet collisions. The Aloha MAC permits end nodes to forward data packets once they wake up and in the event of any collisions, the exponential back-off is applied. The LoRaWAN protocol is responsible for device class allocation. The LoRa specification defines three device classes that the end nodes must operate in, Class A, Class B and Class C. The end node initiates Class A communication which is fully asynchronous. The UL message can be transmitted at any instant, followed by two short DL windows, providing a prospect for bi-directional communication.

After an end node has sent a confirmed message, the end node expects an acknowledgement (ACK) from the NS during the two pre-set timeslots known as “receive windows (RW)”. The gateway either responds with the first RW or the second RW. Unconfirmed messages from the end nodes do not receive an acknowledgement from the NS. Periodic beacons are used to synchronise Class B devices to the network, which opens DL ‘ping slots’ at programmed intervals. The network is provided with the capacity to transmit DL messages with a predetermined latency but this results in added energy consumption in the end node. Class A and B end nodes are largely battery-powered but Class A utilises less power than Class B. Class B devices do not support Class C functionality. Class C devices, in addition to the class A structure of UL followed by two DL windows, further reduce latency on the DL by maintaining the end node receiver continuously listening for responses from the gateway. Because these devices are continually listening, they consume more energy and hence need to be mains-powered. Class C devices do not support Class B functionality.

A LoRaWAN network will always use LoRa as its PHY layer. The LoRaWAN protocol is the suitable MAC layer but different MAC layer protocols can be used. LPWAN requirements such as ACKs, firmware updates, localisation, roaming, and security are all addressed in the LoRaWAN standard.

### 2.3.4 Transmission parameters

LoRa end nodes are set up utilising distinct SF, BW, CR and TP settings, resulting in several permutation possibilities. The LoRaWAN network performance vastly depends on the configuration of these parameters [58]. Determining the settings that curtail the cost of transmission energy whilst sustaining the communication performance requirements is challenging. Configuring these parameters helps to optimise the communication performance as these parameters have an effect on energy utilisation in end nodes. Therefore, it is vital that the battery-powered end nodes select transmission parameters that are appropriate in a LoRa network. Poor choices could cause a hundredfold briefer end node lifetime rendering numerous commercial applications unfeasible as a consequence [59]. Algorithms that can find each node’s optimum transmission parameter configuration are required for the network. Achieving configurations that are optimum involves investigating links with varied settings. LoRaWAN implementations employ static transmission parameter settings with high reliability.

#### 2.3.4.1 Spreading factor

SF is the chip rate divided by the symbol rate. It is the number of raw bits that can be encoded to a symbol. As SF increases the signal-to-noise ratio (SNR) increases, resulting in an increase in sensitivity and range. However, it results in an increase in the packet airtime. The expression $2^{SF}$ denotes the number of chips each symbol can hold [43]. The SF characterises the relationship between the chip rate and the baseband data rate. LoRaWAN SF values range from 7 to 12, which implies that an SF value of 12 increases the strength of the communication signal by increasing the sensitivity of the receiver-equipment, but, the data rate decreases as a result. Conversely, a reduction in the SF causes the data rate to increase, but the message being forwarded requires a higher TP to be properly decoded at the receiver. When the signal is weak, LoRa devices use a higher SF and using a higher SF implies a longer ToA. Also, the distance from the gateway affects SF. The further away the end node is from the gateway the weaker the signal and therefore the higher the SF.

#### 2.3.4.2 Bandwidth

In terms of LoRa modulation, bandwidth is a very crucial parameter. A LoRa symbol comprises of $2^{SF}$ chirps, that spread in the whole frequency domain. A chirp is a signal wherein the frequency increases, called an up-chirp or decreases, known as a down-chirp. The LoRa symbol begins with a set of up-chirps whose frequency increases with time. When it reaches the maximum frequency, it skips back to its lowest frequency and starts over. The down-chirp is the inverse of the up-chirp which starts at the maximum frequency and decreases with time. When it reaches the minimum frequency, it skips back to the maximum frequency and the cycle starts over. BW is a range of frequencies within a given transmission band [60]. High values of BW give higher data rates which imply shorter ToA. This results in reduced sensitivity because of the additional noise that is integrated. A lower BW produces better sensitivity but achieves lowered data rates. Data transmission occurs at a chip rate corresponding to the BW where a BW of 125 kHz corresponds to a chip rate of 125 kilochips per second (kcps). While the BW could be selected ranging between 7.8 kHz and 500 kHz, standard LoRaWAN functions at either 500 kHz, 250 kHz, or 125 kHz (BW500, BW250 and BW125) according to the regional parameters [6].

#### 2.3.4.3 Coding rate

LoRa uses FEC error coding to improve the robustness of the wireless connection. This type of error coding results in additional bits within the LoRa physical layer payload which is controlled by the CR parameter. The LoRa modem uses CR to provide increased protection against bursts of interference and decoding errors. LoRa permits CR settings to be either 4/5, 4/6, 4/7 or 4/8. Setting a high CR value implies that there are more error correction bits which provide better protection for the transmitted data. However, on the downside, it increases ToA which in turn decreases battery life. Receivers which vary CR and hold SF and BW constant can still communicate between them by using an explicit header since the CR of the payload resides in the packet header, which is encoded at CR 4/5 by default [13].

#### 2.3.4.4 Transmission power

In LoRaWAN networks, the power essential for the transmission of a data packet is adjustable as appropriate. Lowering the transmission power will save the battery but shorten the signal range and vice versa. The LoRa radio the TP is adjustable from 4 dBm to 20 dBm in notches of 1 dB. However, in real-life deployments, the TP range is commonly restricted to between 2 dBm and 20 dBm because of hardware limitations. Additionally if the TP levels greater than 17 dBm are experienced, only a duty cycle of 1% can be utilised [59].

### 2.3.5 Applications of LoRaWAN

LoRaWAN technology has a diverse range of applications in various industries because of its flexibility, long-range capabilities, and low power consumption. Industries including manufacturing, healthcare, transportation, agriculture, and energy management have adopted IoT technologies to improve operational efficiency, resource utilisation, and decision-making processes.

#### 2.3.5.1 Smart agriculture

Smart agriculture is one of the application domains where LoRaWAN is commonly utilised to optimise farming operations and improve crop production. LoRaWAN's long-range capabilities, low power utilisation, and scalability make it appropriate for large-scale agricultural deployments. By leveraging the advantages of LoRaWAN in smart agriculture, farmers can optimise resource management, reduce costs, improve crop yields, and make data-driven decisions to enhance overall efficiency and sustainability in farming practices. LoRaWAN enables the deployment of various types of sensors in agricultural fields, allowing farmers to monitor crucial elements such as pH levels, soil moisture, light intensity, temperature and humidity. These sensors collect data and transmit it wirelessly over the LoRaWAN network to a central gateway. With LoRaWAN, farmers can deploy smart irrigation systems that use sensor data to optimise water usage. Based on real-time measurements of soil moisture levels, weather conditions, and plant water requirements, the system can automatically control irrigation schedules, minimising water waste and maximising crop health [61]. LoRaWAN-connected devices, such as cameras and drones, could be employed in monitoring crop health, growth stages, and detecting signs of diseases or pest infestations. These devices capture images or collect data using various sensors and transmit it to the gateway for analysis and timely intervention [62, 63]. LoRaWAN can be employed to monitor livestock by attaching sensors to animals. These sensors are able to track factors like location, temperature, and activity levels, providing farmers with valuable insights into the health and behaviour of their livestock. It helps in detecting anomalies, managing feeding schedules, and ensuring the well-being of the animals [64]. LoRaWAN can facilitate environmental monitoring in agricultural areas. Weather stations connected via LoRaWAN can collect data on temperature, humidity, wind speed, rainfall, and solar radiation, empowering farmers to make well-informed planting, harvesting, and pest control decisions [65]. LoRaWAN-based asset tracking systems could be utilised in monitoring the location and movement of agricultural equipment, machinery, and valuable assets. This helps in preventing theft, optimising resource allocation, and streamlining logistical operations.

#### 2.3.5.2 Smart healthcare

In the healthcare industry, LoRaWAN can be utilised for various smart healthcare applications, enabling remote monitoring, efficient resource management, and improved patient care. By leveraging LoRaWAN technology, healthcare providers can improve patient outcomes, enhance operational efficiency, and deliver more personalised and proactive care. LoRaWAN enables the deployment of remote monitoring devices capable of collecting vital physiological indicators from patients in their homes or healthcare facilities, such as heart rate, temperature, oxygen levels and blood pressure. This data is transmitted securely over the LoRaWAN network to healthcare providers, allowing them to monitor patients' health status and detect any abnormalities in real time [66]. LoRaWAN-based asset tracking systems can help healthcare facilities track the positioning and movement of medical equipment, for instance, infusion pumps, wheelchairs, and defibrillators. By attaching LoRaWAN-enabled tags to these assets, staff can quickly locate them when needed, optimise equipment utilisation, and reduce inventory costs [67]. LoRaWAN can support applications aimed at ensuring the safety and well-being of elderly individuals such as wearable devices capable of monitoring activities of daily living, detecting falls, and sending alerts to caregivers or emergency services when necessary. This enables independent living while providing a safety net for the elderly [68]. LoRaWAN can be utilised for smart medication management systems. Connected pill dispensers or medication adherence devices can remind patients to take their medication at the right time and track their adherence. The data is transmitted over LoRaWAN to healthcare providers or caregivers, who can monitor medication compliance and provide timely interventions if needed.

#### 2.3.5.3 Smart cities

LoRaWAN can play a vital role in creating efficient and sustainable urban environments, enabling cities to become more sustainable, efficient, and liveable. LoRaWAN can facilitate smart parking systems by deploying sensors that detect the availability of parking spaces in real time. These sensors communicate wirelessly over the LoRaWAN network, allowing drivers to find vacant parking spots quickly. This reduces traffic congestion and emissions, leading to improved traffic flow and a better parking experience for residents and visitors [69]. LoRaWAN-enabled smart waste management systems can optimise garbage collection routes and schedules. Sensors installed in trash bins can monitor fill levels, enabling waste management authorities to optimise collection routes and reduce unnecessary pickups. This leads to cost savings, reduced vehicle emissions, and improved overall efficiency in waste management operations [70]. LoRaWAN can be utilised for intelligent street lighting systems. Connected streetlights equipped with LoRaWAN connectivity could be remotely controlled and managed. They can automatically adjust their brightness based on ambient light levels or motion detection, leading to energy savings and improved safety in public spaces [71]. LoRaWAN can enable smart water management systems in cities. Sensors placed in water supply infrastructure, such as pipes and reservoirs, can monitor water quality, pressure, and consumption. This data helps identify leaks, optimise water distribution, and detect abnormalities, contributing to efficient water resource management [72]. LoRaWAN can support smart metering for utilities such as electricity, gas, and water. LoRaWAN-connected meters can transmit consumption data wirelessly, eliminating the need for manual readings. This enables accurate billing, better resource management, and the ability to detect anomalies or leaks promptly [73].

#### 2.3.5.4 Smart industries

LoRaWAN can be leveraged to enable smart industry applications, optimising processes, improving efficiency, and enabling predictive maintenance. LoRaWAN-connected sensors can be deployed to regulate the health and performance of industrial machinery and equipment. These sensors gather data on parameters including but not limited to temperature, vibration, pressure, and energy expenditure. The data is transmitted over LoRaWAN to a central system where it can be analysed to detect anomalies, predict failures, and schedule maintenance proactively, reducing downtime and optimising maintenance operations [74]. LoRaWAN can enhance supply chain visibility and efficiency in industrial settings. By using LoRaWAN-enabled sensors and gateways, businesses can track and monitor the movement of goods, monitor storage conditions (e.g., temperature, humidity) during transportation, and receive real-time updates on delivery status. This improves inventory management, reduces loss or spoilage, and enables better coordination with suppliers and customers. LoRaWAN can support smart energy management systems in industrial facilities. By deploying LoRaWAN-connected meters and sensors, businesses can monitor and optimise energy consumption, track power quality, and detect anomalies or inefficiencies. This enables energy cost reduction, better resource allocation, and compliance with energy efficiency regulations [75].

#### 2.3.5.5 Smart buildings

In the context of smart buildings, LoRaWAN can play a significant role in enabling various applications that enhance energy efficiency, occupant comfort, and operational efficiency. LoRaWAN can support smart energy management systems in buildings. By deploying LoRaWAN-connected sensors and meters, building managers can monitor and optimise energy consumption in real time. These sensors can measure electricity usage, water consumption, temperature, humidity, and other parameters. The data is communicated over LoRaWAN to a central management system, allowing for better energy monitoring, demand response, and identification of energy-saving opportunities [76]. LoRaWAN can enhance security and safety measures in buildings. Connected surveillance cameras, access control systems, and intrusion detection sensors equipped with LoRaWAN connectivity can transmit alerts, video footage, and data to a central monitoring system. This enables real-time monitoring, quick response to incidents like fire hazards, and enhanced security for occupants and assets [77].

### 2.3.6 Impact of multiple gateways on LoRaWAN

Components of the LoRaWAN architecture such as the number of EDs and GWs connected to the network impact the overall network performance. The LoRaWAN Standard does not allow direct communication between EDs, thus, data packets require to be transmitted through a GW both for uplink and downlink transmissions. The ADR protocol, which is an essential component of LoRaWAN, allows ED transmission parameters to be dynamically adjusted to adapt to network conditions to improve the network's lifetime. Because end devices rely on gateways to transmit data to the internet, gateway placement is important in ensuring ED coverage. Proper gateway placement aids in determining the overall number of gateways required in the network and their optimal locations [78]. This helps to reduce network congestion and enhance throughput although this will come at an increased deployment cost. The throughput of LoRaWAN network is influenced by the distance of the EDs from the GW. EDs placed at the network edge can have a throughput as low as 100 bits per second and 2 kilobits per second for EDs close to the GW [79]. The effect of interference in a single GW LoRa network was studied in [80]. Their results show that coverage probability decreases exponentially as the number of EDs increases caused by co-SF interference, that is, interference of signals transmitting using the same spreading factor. According to [59] the GW has the ability to handle a high density of EDs for an average traffic load but would not guarantee the QoS for "bursty" traffic. This problem could be mitigated by increasing the number of gateways in the network. The work in [81] demonstrates how allocating spreading factors among EDs has a significant impact on the uplink capacity and how gateway placement needs careful planning to meet various application requirements. In [82] the authors proposed an ADR algorithm that determines the link quality by obtaining information from multiple GWs to allocate appropriate spreading factor and transmit power of EDs. The proposed approach illustrated an improvement in throughput, energy efficiency and battery life. ADRopt is an adaptive data rate scheme that was developed in [83]. It improved the data extraction rate using multiple gateways reaching high levels of reliability in the LoRaWAN network, even in harsh network conditions. The authors in [84] reviewed the methods that are used in gateway placement. Different QoS requirements determine which approach of gateway placement will be used, for example, collision probability reduction [85], throughput optimisation [86], and scalability [87]. In [88] the authors used different strategies to analyse the optimum placement of sixteen and twenty-five gateways. Using Fuzzy C-means, they improved the performance of sixteen gateways to match that of twenty-five gateways with a similar packet delivery ratio.

In [89] the authors analysed the impact of the GW and ED node density on the performance of the LoRaWAN network through extensive simulations in ns-3. They investigated how a fixed number of end devices can be served by an increased number of gateways. Evaluation of the network performance of LoRaWAN was conducted in this work, with different parameters and suitable metrics. A simple LoRaWAN network with a small number of nodes consisting of up to 7 GW nodes, one NS node and up to 250 ED nodes was used. The considered network covered an area of 1000m x10000m and the end devices were placed in a uniform random distribution. The gateways were located within the network using the hexagonal grid allocation method. Packet delivery ratio, packet success rate, and energy consumption were used to show the performance with respect to the number of EDs and a different number of gateway nodes. They were able to demonstrate that the LoRaWAN architecture scales well owing to the fact that increasing the number of gateways improves the coverage and reliability of the uplink. The results showed a decrease in energy consumption and an increase in PDR with respect to the increase in GW density as shown in Figure 2.3 and Figure 2.4 respectively. The findings from our work may be employed for the optimisation of the LoRaWAN ADR performance by properly selecting the optimal number of gateways for a given network.

Despite the overall rise in energy consumption due to increased ED node density, it is noteworthy that energy utilisation decreases in relation to the expansion of GW nodes. The reduction in total energy consumption can be attributed to the significant impact of the ADR algorithm, which optimises transmission power based on the proximity of EDs to their nearest GW node. Consequently, more end nodes are capable of transmitting data at lower spreading factors (SF). Consequently, the incorporation

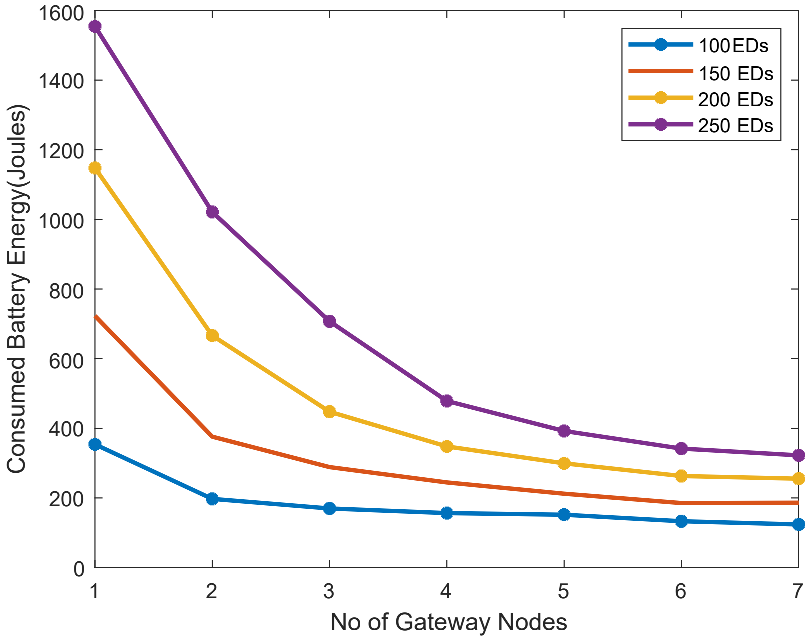


**Figure 2.3.** Comparison of total energy consumption.

of additional GW nodes is an effective approach for minimising energy consumption within the LoRaWAN network. Lower SF values lead to higher data rates and shorter time-on-air, resulting in reduced energy expenditure.

The increase in the number of gateway nodes yields notable enhancements in packet delivery ratio performance. The reduction in the spreading factor at the EDs, caused by the increased number of GWs, leads to a decrease in time-on-air for data transmissions. As a result, the number of collisions decreases, positively impacting the PDR of the network given a constant network radius. For this network, it can be observed that beyond four gateway nodes, it becomes challenging to discern any performance changes concerning the density of the EDs. Therefore, alternative metrics would need to be employed to perform a more detailed analysis of the network's behaviour.

From the results, the following findings and observations were established.

- The performance of LoRaWAN significantly improves with respect to the increase of GW nodes. It is important to select an optimal number of gateways without compromising network performance.

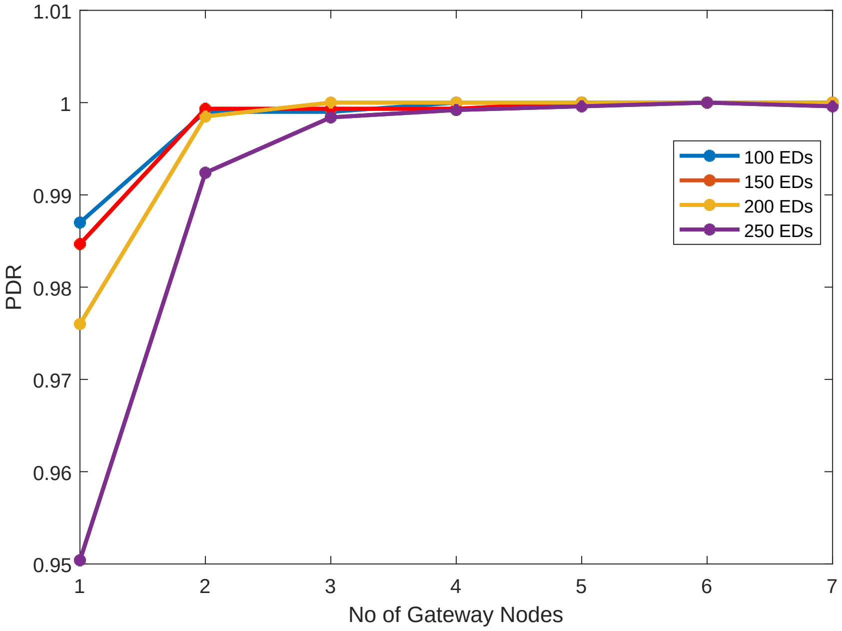


**Figure 2.4.** Comparison of packet delivery ratio.

- The network performance decreases with respect to the increase in ED node density. There is an inverse relationship between the number of EDs and network performance. Determining the optimal capacity of the network is important.
- The ADR algorithm contributes significantly to the decrease in total energy consumption with the dynamic adjustment of the transmission parameters with respect to the changes in GW node density.

## 2.4 ADAPTIVE DATA RATE IN LORAWAN

An essential LoRaWAN feature is the ADR scheme which seeks to minimise battery usage and maximise throughput by altering the data rate and TP for each end node in the LoRa network. Data rate adaptation in a LoRaWAN allows easy scalability of the network, by the addition of gateways. Furthermore, the use of ADR significantly increases the capacity of such a network, since the data packets that are transmitted using different SFs are orthogonal and can be transmitted concurrently [90]. An ADR scheme was developed into LoRaWAN to be able to manage the end nodes' transmission parameters to improve the packet delivery ratio (PDR). The ADR controls transmission parameter settings for the UL data from the end node to the gateway. The ADR algorithm is responsible for managing the data rate and transmission power of end nodes based on the link budget estimation in the UL message and the maximum SNR required for accurately decoding data packets at the existing data rate. In the case of fixed end nodes, the NS manages the ADR depending on the history of the UL packets received, referred to as "Network-managed ADR or Static ADR". The network-based ADR approach does not work for mobile end nodes because of channel attenuation which occurs as the device moves. Where mobile end nodes are concerned, ADR is performed "blindly" on the end node side known as "Blind ADR".

LoRaWAN networks employ adaptive modulation techniques with multiple channel, multiple modem transceivers in the gateway to receive multiple messages from the channels. Each specific signal uses a unique SF, with orthogonal separation provided by the spread spectrum. This technique presents advantages in data rate management [91]. LoRaWAN's ADR scheme dynamically adapts the transmission parameters aiming to prolong battery life and maximise throughput. This is done by varying the data rate and TP for each end node in the LoRa network. ADR improves the data rate, ToA, and energy utilisation. In LoRaWAN, varying the SF adjusts the data rate of the end nodes thus optimising the throughput. Nevertheless, the ADR must be utilised cautiously since the collision probability, which directly influences throughput, is affected by the change in SF. The ADR algorithm was established for stationary end nodes and stable radio channel environments [6]. The ADR scheme bases its choice of data rate on the past performance of each end node. The LoRaWAN MAC layer contains four different commands for ADR shown in Table 2.3.

**Table 2.3.** LoRaWAN ADR commands.

| **Characteristic** | **Description** |
|---|---|
| ADR | End node sets this bit requesting the gateway to control its data rate |
| ADR=1 | NS will control the end nodes data rate |
| ADR=0 | NS will not control the end nodes data rate |
| ADRACKReq | Allows end nodes to periodically receive confirmation |
| ADRACKReq=1 | NS should respond to confirm receipt of UL data |
| ADRACKReq=0 | Confirmation of receipt of UL data not required |
| LinkADRReq | Transmitted by NS to request end node to change its transmit parameters |
| LinkADRAns | Transmitted by nodes in response to LinkADRReq command |
| LinkADRAns=1 | Transmit parameters successfully set |
| LinkADRAns=0 | Command is discarded |

Because end nodes have limited battery capacity, the performance of LoRaWAN networks is affected by power consumption. The fact that the end nodes must accommodate specific data rates further compounds the power limitation challenge because the SNR levels must be above certain thresholds as well as the power levels. Additionally, the end nodes have to respond to the channel conditions in the network. This means end nodes must have the ability to regulate the transmission rates and power levels appropriately [31]. A LoRa gateway can listen for UL messages simultaneously on every SF and BW permutation, whilst the end nodes are capable only of eavesdropping on a single fixed SF and BW sequence successively. An end node may use any set of transmission parameters to communicate with the gateway without handshaking. Message transmission from gateways to end nodes occurs on a programmable offset from the UL data rate in the first RW, and typically with the highly robust setting, the lowest data rate in the second RW.

### 2.4.1 ADR on the end device side

An end node notifies the gateway that it requires the use of ADR by configuring the ADR bit in the frame header. Once ADR is configured, the NS uses LinkADRReq, the MAC command that controls the end node's data rate and TP. The end node will respond with the LinkADRAns command to indicate acceptance or rejection of the new settings. The ADR algorithm comprises of an acknowledgement system which is devised to permit end nodes to intermittently verify that the NS received the UL message. If an ACK message is not received by the end node, the end node will switch to a lower data rate in an attempt to regain connectivity. The permutations of the transmission parameters produce a potential 6720 potential transmission settings of which the LinkADRReq command can only select from a subset of eight data rate settings and six transmission power settings [6]. Even though LoRaWAN stipulates a transmission parameter signalling scheme via the LinkADRReq command, there is no description available of how the communication should be handled. The specification does not state how the NS should instruct end nodes concerning adapting the data rate when to change a setting, or the order in which the settings should be changed [60]. The NS is left with the responsibility to implement ADR. The end nodes also have the capability of managing the ADR transmission parameters using the ADR system that is nested on the end node side. This means that the ADR scheme can run asynchronously at the NS side and the end node side.

As stated in the LoRaWAN standard, there are two parameters that have been specified, namely ADR_ACK_LIMIT and ADR_ACK_DELAY. The default values for these parameters have been set to 64 and 32, respectively. For every UL packet that an end node transmits, ADR_ACK_CNT counter is increased by one. Once the ADR_ACK_CNT becomes equal to ADR_ACK_LIMIT without any DL response, the end node sets the ADRACKReq bit and waits for an ACK from the gateway for the subsequent ADR_ACK_DELAY UL packets. In the absence of an ACK ahead of ADR_ACK_DELAY UL message, the end node decreases the data rate attempting to re-establish network connectivity. In accordance with the latest release, end nodes initially increase TP to secure connectivity. If that is inadequate, the end nodes then reduce the data rate as an element of the subsequent stage [14]. Figure 2.5 outlines the flow of the ADR scheme executed at the end node.

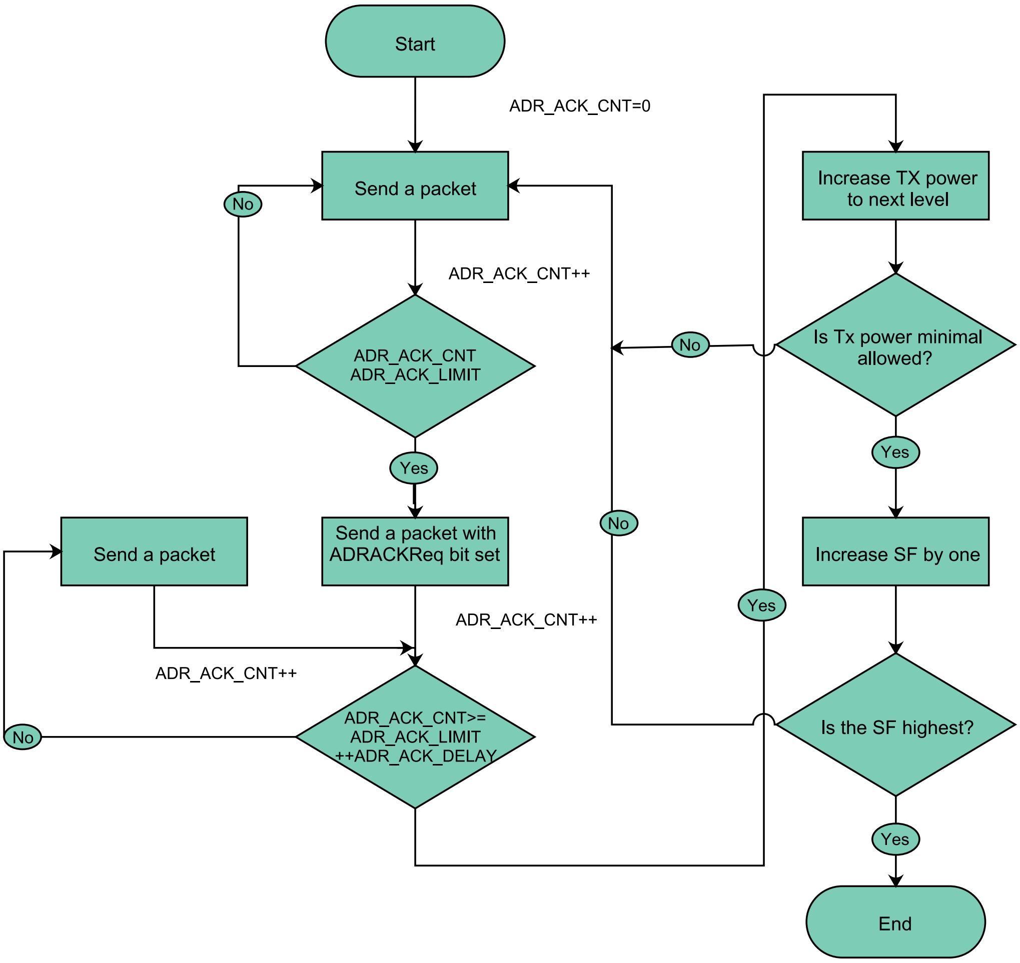


**Figure 2.5.** ED-side adaptive data rate flow. Taken from [14], (c)2018, Authors.

### 2.4.2 ADR on the network server side

On the network server side, the determination of the Signal-to-Noise Ratio (SNR) value involves channel estimations based on the signal-to-noise ratio of the twenty most recently received data packets (ULs), starting from the instant the ADR bit is set on the ED side. Various ADR schemes employ different methods to obtain the SNR value from these ULs, including selecting the maximum value among the twenty ULs, choosing the minimum value from the twenty ULs, or calculating an average of the UL messages [92–94]. In [95], the focus is on investigating the impact of these three methods for obtaining the measured SNR value within the ADR scheme. Once the SNR value is determined, the “margin” is calculated, which represents the measured SNR minus the required SNR to demodulate a packet given the data rate, as expressed in (2.2). The margin determines the feasible adjustments to optimise the ADR scheme.

$$SNR_{margin} = SNR_{avg} - SNR_{required} - D_{margin}\,, \tag{2.2}$$

where $SNR_{avg}$ is the average SNR of the packets in the ReceivedPacketList, and $SNR_{required}$ is the minimum SNR threshold, and $D_{margin}$ is the device margin.

Once the margin is computed, $N_{step}$ which characterises the number of iterations the algorithm is performed, is computed by (2.3).

$$N_{step} = int(SNR_{margin}/3)\,, \tag{2.3}$$

where *int* is the integer part of the result obtained.

In the scenario where $N_{step}$ equals 0, the ED is already utilising the optimum configuration for both SF and TP. However, if $N_{step}$ surpasses 0, it indicates the presence of a reasonable scope for optimising these two parameters. The optimisation process involves two steps. Firstly, the SF is systematically decreased until it reaches the defined minimum threshold. Secondly, the TP is decreased by 2 units iteratively towards the specified minimum limit of 2 dBm. Conversely, when $N_{step}$ becomes negative, only the TP is incremented by 2 units iteratively until it reaches the maximum limit of 14 dBm.

### 2.4.3 Impact of SNR averaging on ADR

To evaluate the impact of SNR averaging on standard ADR performance in [95], the network comprised 200 EDs which periodically generated packets and transmitted through up to 7 GWs to a network server. This was done by evaluating the effect of modifying the calculation of $SNR_{value}$ given in (2). The total energy consumption in LoRaWAN networks is dependent on the energy consumed in each state of the EDs, and it is the sum of the battery energy utilised by all EDs over the course of the simulation.

#### 2.4.3.1 Impact on total energy consumption

In Figure 2.6, we present the performance of three different history averaging methods for the ADR implementation in LoRaWAN, specifically in terms of the total energy utilisation of the EDs. Despite ADR-SNR-MIN demonstrating better performance in other considered metrics, it consumes more energy compared to the other two methods. This suggests that ADR-SNR-MIN may not be the most energy-efficient option for LoRaWAN deployments, even though it may offer advantages in terms of other performance factors. Contrastingly, ADR-SNR-MAX outperforms the other two methods in terms of energy expenditure. The ADR algorithm optimises transmission power and spreading factor according to the proximity between the EDs and their closest GW. By utilising additional GWs, the energy utilisation of the LoRaWAN network can be minimised. The results highlight the importance of considering energy efficiency when selecting the appropriate history averaging method for ADR implementation in LoRaWAN networks. While other metrics may be prioritised in certain scenarios, the overall energy utilisation is a vital factor in ensuring the longevity and sustainability of the network

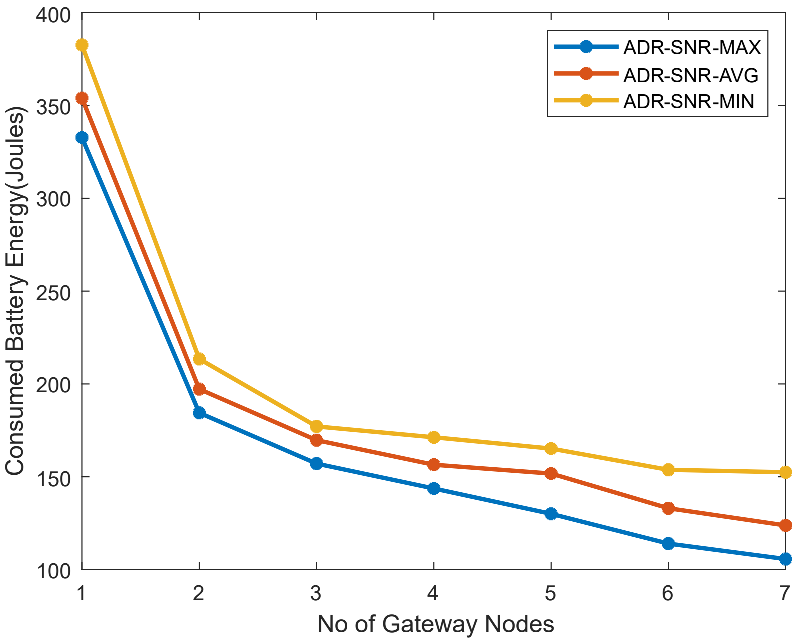


**Figure 2.6.** Total energy consumption.

### 2.4.3.2 Impact on successful reception rate

The successful reception rate in LoRaWAN networks is classified as the ratio of total packets sent to the packets received successfully at the GW. In Figure 2.7, we present the performance of three different history averaging methods for the ADR implementation in LoRaWAN, specifically in terms of the successful reception rate at the GW node. Among the three methods, ADR-SNR-MIN exhibits a notably high successful reception rate compared to the other averaging methods. This indicates that a larger proportion of packets sent are successfully received at the GW. Despite its higher interference rate in comparison to its counterparts, ADR-SNR-MIN proves to be the best-performing method in terms of successful reception rate. While a higher interference rate may suggest potential challenges in terms of packet transmission, the superior successful reception rate of ADR-SNR-MIN demonstrates its effectiveness in mitigating the impact of interference. This highlights the importance of considering the overall performance and reliability of the network, rather than solely focusing on the interference rate.

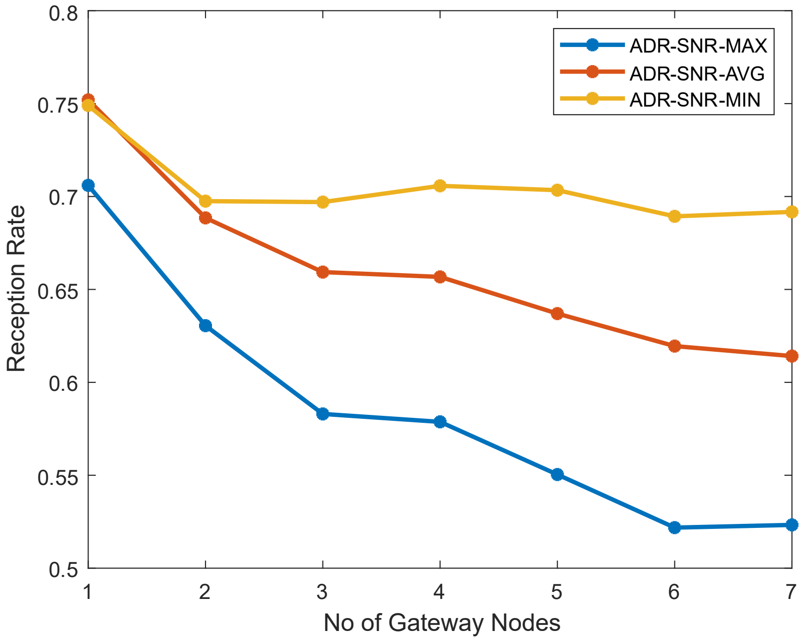


**Figure 2.7.** Successful packet reception rate.

### 2.4.3.3 Impact on interference/collision ratio

The failure of packet reception at the GW in LoRaWAN networks can be attributed to interference caused by overlapping packets. In Figure 2.8, we present the performance of three different history averaging methods for the ADR implementation in LoRaWAN, specifically in terms of the Interference/Collision Rate. Among the three methods, ADR-SNR-MAX demonstrates the lowest

Interference/Collision Rate. This can be attributed to its larger SNR margin compared to the other two methods. The increased SNR margin provides a greater tolerance for interference and collisions, resulting in a lower rate of occurrence. Furthermore, it is observed that the Interference/Collision rate decreases as the number of GW nodes increases. This is due to the availability of more transmission channels. By increasing the number of GW nodes, the network can distribute the traffic across multiple channels, reducing the likelihood of interference and collisions between packets.

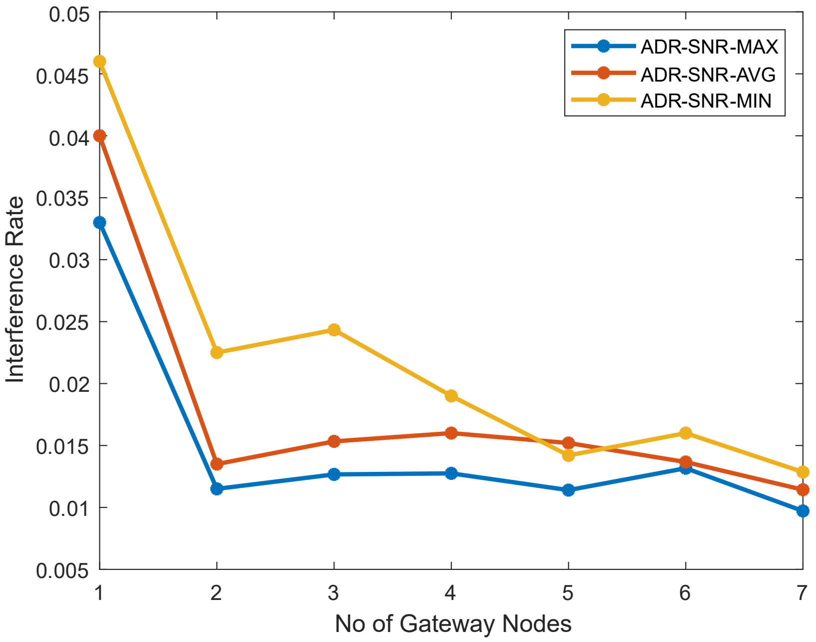


**Figure 2.8.** Interference/collision rate.

Based on the findings presented, it is evident that the ADR-SNR-MIN packet history averaging method shows better performance in comparison to the other two methods regarding successful reception rate. However, it is worth considering other aspects like energy consumption, interference, and collision rate. While ADR-SNR-MIN demonstrates a better successful reception rate, it consumes more energy compared to the other methods. This higher energy consumption should be taken into account when considering the overall efficiency and battery lifetime of the LoRaWAN network. Furthermore, ADR-SNR-MIN exhibits a higher interference and collision rate compared to the other methods. This indicates a potential trade-off between successful packet reception and the level of interference and collisions experienced in the network. The impact of this increased interference and collision rate on the overall network performance and reliability should be carefully evaluated, especially in scenarios with high network traffic or dense deployment of devices. Therefore, while ADR-SNR-MIN shows advantages in terms of successful reception rate, it is important to consider the trade-offs associated with energy consumption and interference/collision rate. A comprehensive analysis considering all these factors will facilitate the selection of the most suitable packet history averaging method for a specific LoRaWAN deployment, ensuring a balance between performance, energy efficiency, and network reliability. The findings of this study make a contribution to an enhanced knowledge of the adaptive data rate's effect on the performance of LoRaWAN networks, offering insights into its suitability for diverse IoT applications. This combined with other techniques can improve the resource allocation of the LoRaWAN ADR algorithms.

## 2.5 OPTIMISED ADAPTIVE DATA RATE SCHEMES

Having an exceptional ADR scheme gives vendors a competitive edge, as such they maintain their applications confidential. Thankfully, there is an open-source network manager that made its ADR algorithm publicly available, The Things Network [96]. This algorithm is based on Semtech's recommended algorithm for rate adaptation. The LoRaWAN ADR is a scheme used to optimise the network's data rates, ToA and energy consumption. To maximise the battery life of the end nodes and global system capacity, the LoRaWAN NS controls the data rate and TP for all the end nodes independently through an ADR scheme. Several data rate adaptation schemes have been propositioned in literature that attempt to enhance communication performance. In literature, ADR scheme has been modified and implemented to meet different objectives in the LoRaWAN targeting network performance metrics. We review the body of work that employs ADR to improve metrics such as scalability, throughput, channel access, received signal strength (RSS) and energy efficiency.

### 2.5.1 Scalability

In LoRaWAN networks, ADR control is enabled to keep network connectivity by providing numerous data transmission rates. The condition of the RF connection is determined through the receive status of the ACK packet in LoRaWAN through link errors. This, however, does not indicate a congested network but may result in inefficiencies in transmitting data due to long transmission delays. Since congestion is not considered a connectivity problem, decreasing the data rate by substituting the modulation system is inappropriate. In [33] the authors developed an ADR scheme that attempts to preclude extraneous data rate management using logistic regression. The proposed scheme recognises the congestion levels of the network by learning and then applying the result to control the data rate. The method uses data rate, RSS, and number of connections at the gateway as characteristics for learning. Evaluation of these attributes provides the congestion estimation. When the congestion is projected, the proposed algorithm revises the back-off time rather than reducing the data rate, adjusting latency instead of reducing throughput. This results in the improvement of the accuracy of data rate control and network efficiency. The NS performs the learning and delivers the results to the end nodes to predict congestion. The computation for learning is done in a centralised machine. The strength of this approach is that it considers the level of congestion in the network, unlike the legacy ADR scheme. The drawback of this approach is that the process demands an ACK DL message for each transmission. Because DL traffic has a negative effect on UL throughput, the PDR decreases as a result [97]. Future research could look at studying distributed learning of the end nodes. Other methods of optimisation could be applied to predicting congestion.

Framework for LoRa (FLoRa) was developed in [34], wherein the authors dynamically manage link parameters for scalable and efficient network operations. The authors developed a non-proprietary scheme for end-to-end LoRa simulation in OMNeT++. They considered a distribution of SFs on the average SNR values from several uplink packets received at the gateway as opposed to the highest SNR used in the standard ADR scheme. They use comprehensive simulations to demonstrate that ADR effectively increases the PDR, maintaining low energy utilisation under stable RF conditions. Their results showed that adjusting channel conditions had a severe effect on the performance of the ADR scheme, hence the modification of the link quality indicator, and the introduction of a transmission policy to increment TP at the end nodes. The proposed ADR scheme achieved at least thirty percent better PDR compared to the standard ADR scheme in the cases of moderate variable channel conditions. The proposed scheme showed that appropriately configuring SFs and TPs could boost the network capacity and reduce energy utilisation, based on the overall knowledge of the network. It implements an ADR algorithm wherein end nodes could dynamically update their SF and TP. Although the proposed algorithm shows a significant increase in reliability and energy efficiency, there is a drawback. Waiting for twenty frames in order to adjust the scheme may be too long. For dense networks, link-based adaptation is inadequate. Future work could consider incorporating collision probability and the distribution of parameters in the network. Balancing the link budget for every link and PDR of the entire network could further improve scalability.

Reynders et al. [17] proposed a MAC layer protocol RS-LoRa which distributes SFs and TPs to reduce the capture effect and inter-SF collisions and improve network reliability and scalability. They introduced a two-step lightweight scheduling method that divides end nodes into clusters, where identical TPs are applied in each cluster to diminish the capture effect. First, the end nodes get recommended by the gateway's coarse-grained scheduling to apply distinct SFs and RSS to allow concurrent transmission, therefore reducing packet collisions. The gateway broadcasts beacons to the end nodes before the nodes can send any packets. Depending on the coarse-grained information supplied by the gateway, the end nodes select the parameter combination and channel that best suits the nodes. Using this approach, the reliability of the network is improved by reducing packet error rate (PER) up to twenty percent compared to standard LoRaWAN using NS-3 simulation. Improved network reliability improves network scalability which in turn contributes to an improvement in the throughput. Network performance improves significantly when there are many end nodes in the network to the tune of one thousand, for example. Although the light-scheduling approach improves reliability and scalability, there is an introduction of additional energy consumption as the end nodes need to listen for the beacon from the gateway before sending a packet. The approach does not eliminate packet collisions entirely because uplink messages could still collide with beacons from other gateways. Because the approach uses Aloha, it also means collisions cannot be eliminated. Future work could look at using a different MAC protocol to improve PER.

The authors in [98] modified the standard ADR algorithm to produce an expansion of the network scalability, fairness between nodes, PDR and robustness to dynamic channel conditions. The algorithm facilitates the system to optimise SF and TP for each end node with the purpose of increasing the reliability of communication and optimising energy usage at the end nodes. The authors recommend varying data rates before increasing TP, averaging of SNR history, and accounting for hysteresis. With empirical evaluation of the relationship between PER and SNR, the authors find a channel model which they subsequently applied in MATLAB simulations. Certain alterations of the algorithm, enable the achievement of improved error performance in rough channels resulting in the reduction in the number of retransmissions and DL commands from the NS. The algorithm decreases the data rate before increasing TP whenever a given fixed threshold is exceeded. They introduce variable hysteresis into the algorithm which mitigates against the effect of collisions and duty cycle limitations. The proposed algorithm reduces the number of data messages in the UL as well as the MAC command messages in the DL and achieves superior error performance in poor condition channels. This enables the extension of the network range. The drawback of this algorithm is that the simulation model used does not consider large complex networks.

A model that optimises attenuation and collisions in order to optimally allocate the SF was proposed in [99]. The model aims to optimise the number of end nodes distributed in the network whilst assigning SFs that maximise transmission quality. They consider physical capture and imperfect SF orthogonality whilst ensuring a specified probability of successful transmission to every end node within the network.

The approach considers an authentic propagation model which considers physical capture that could surface at the gateways. They consider inter-SF and intra-SF interference for each node as a potential for packet collisions. However, it assumes that the density of the end nodes within the gateway range is uniform, which is not realistic. End nodes covering areas of several square kilometres would be highly non-uniform. This mathematical model needs to be validated by simulation to quantify the

Bor et al. [100] proposed a dynamic transmission scheme and made the network denser by adding more gateways. They experimentally observed the capture effect of LoRa, that when signals with the same SF are transmitted simultaneously, the strongest signal suppresses the weaker signals when the difference in power is adequately large. They developed a LoRa simulator (LoRaSim) and analysed the LoRa scalability threshold in fixed settings. They modelled the capacity of such networks by introducing the Data Extraction Rate (DER) metric, modelling uplink behaviour and proposed a mathematical model for transmission range dependent on the experimental data gathered. They concluded that the network with a single gateway and moderate transmission parameters did not scale well, whilst those with dynamic adaptation of transmission parameters or multiple gateways tended to scale better. They found that network scalability increases when the parameters configuration minimises ToA. This model, however, overestimates the link attenuation of LoRa signals in free space. The model needs on-site measurements which are difficult to obtain since most of the area of coverage comprises of conventional connections, classified as connections with dynamic temporal link attributes. Although the use of multiple gateways outperforms existing results, optical placement of the gateways consistent with the category of application would further improve the performance.

Finnegan et al. [101] presented significant improvements aimed at the end node and gateway that decrease the convergence time for LoRa nodes to attain the optimum data rate. They extended the LoRaWAN component in NS-3 by including ADR, thus allowing the simulation of lifelike LoRaWAN networks by implementing novel improvements in this module. The simulations demonstrate a significant decrease in convergence time for the end nodes due to the modifications. This leads to an increase in global PDR for the network in a dynamic network environment. The authors presented an evaluation of the behaviour of the standard ADR scheme and proposed a new variant of the scheme with improvements that enhance performance in all cases whilst maintaining the ability to be efficiently integrated into an existing LoRaWAN network.

The authors in [102] employed SF allocation as a tool to increase LoRa network capacity. They defined an optimisation problem for SF allocation by maximising packet success probability (PSP) to maximise end node connectivity. In their scheme, the authors consider both inter- and intra-SF interference when assigning the SF allocation. The interference considerations are incorporated through the capture effect when the signal of interest maintains a signal-to-interference (SIR) which surpasses a certain threshold. The propositioned approach controls the SF distribution dependent on the assignment distances resulting from the solution of the optimisation problem instead of the coverage distances derived from the physical layer LoRa sensitivities. The authors use stochastic geometry to determine the average system PSP. They assign SFs to end nodes with two considerations:(a) the received power from the end node must surpass the receiver sensitivity threshold for the allotted SF; and (b) the SIR for the end node must similarly eclipse the accurately decoded SIR threshold for that SF. Although the complexity is high for multiple variables, the global optimisation solver can be used to solve the problem.

A method to improve the capacity of Mesh LoRa networks using network clustering which is based on SF was proposed in [103]. They used a Tree-Based SF Clustering Algorithm (TSCA) which allocates nodes to numerous subnets. They use the LoRa transmission parameter selection to create mesh networks. The approach is rooted at the gateway in which every tree is a subnet with a different SF to enable simultaneous transmissions. TSCA balances the traffic load to avoid bottlenecks at the subnet using SF capacity estimation considering the number of nodes, data rates and hop count of the subnets. Minimising the number of hops and the delay is the objective, since higher SF values result in more airtime, leading to an increase in the end-to-end delay. According to the authors, their results showed an improved performance in contrast with the SF allocation in a single-hop LoRaWAN network. Future research could involve a faster approach to predicting connectivity that would utilise the quickest data rate for the connectivity prediction of all the SFs.

### 2.5.2 Throughput

ADR can be used to improve network throughput by improving DER. Cuomo et al. [104] propose two algorithms of incremental complexity EXPLoRa-SF and EXPLoRa-AT. EXPLoRa-SF is a heuristic which attempts to equally distribute SFs to the end nodes in the gateway's radio range, only restricted by their received signal strength indicator (RSSI) values and relevant thresholds. EXPLoRa-AT on the other hand, propagates impartial allotment of the ToA between the end nodes in the network. The proposed scheme does not configure the SF on the basis of distance and received power measurement, but instead considers the quantity of linked end nodes, enabling the equalisation of the ToA of the packets in each SF. EXPLoRa-AT guarantees equalisation of the RF channel utilisation by the end nodes by leveraging the use of multiple SFs in order to have orthogonal sub-channels. The two algorithms combine SF orthogonality and radio range visibility to expand the density of end nodes with concurrent transmission in the grid, reducing collisions, improving DER and ultimately improving throughput. The ordered waterfalling technique is used for the even distribution of channel load between the end nodes in the system. For dense networks, the algorithms substantially improve data rates and robustness. Simulation of EXPLoRa-SF and EXPLoRa-AT in "LoRaSim" has a superior performance compared to the standard ADR. These two algorithms are implemented using one gateway. The drawback of this approach is that it is designed under the assumption that end nodes transmit with a uniform data rate and payload. The work in [105] attempts to address this drawback. There are circumstances where the assigned SF in EXPLoRa-SF does not adhere to the restrictions stipulated in LoRaWAN that degrade performance. Also, the proposed approach in [104] does not support implementation with multiple gateways which is an open gap for future research.

A contention-aware ADR scheme, developed by [32] traces the distribution of end nodes for every SF and seeks to expand the number of gadgets utilising low SFs. The authors attempt optimisation of throughput in networks where the same SF can be used by a huge number of end nodes. The scheme uses constrained optimisation and defines the total throughput as an objective function with respect to the quantity of end nodes utilising specified SFs. The authors develop the theoretic optimum throughput which could be accomplished by changing only the data rate of the end nodes. They adopt the gradient projection method to solve the constrained optimisation problem, which enables the gateway to effectively obtain the optimum configuration subject to the constraints irrespective of the number of end nodes implemented in the system. When numerous end nodes have analogous link quality, specifically in relation to the partial use of the SF, the propositioned approach achieves significantly better throughput than the existing scheme due to the load-balancing effect. The strength of the approach is factoring in the contention issue in optimising ADR. Although this approach improves throughput, the transmission success ratio of the end nodes declines, so if reliability is more important than throughput in an application, this approach would not be sufficient. For future research, a more comprehensive evaluation and efficient solution for the SF update via DL is an area that is open. An optimisation technique can be developed that considers the transmission success ratio at the same time thus extending the solution to the multi-objective optimisation problem.

A fair adaptive data rate algorithm (FADR) that calculates data rate and TP assignment with the purpose of achieving fairness in data rate and reducing collisions between the end nodes is propositioned in [106]. The algorithm uses RSSI values in its computations while deciding SF and TP allocations to maximise DER among all end nodes. The authors propose a “region concept” to assign SFs depending on the RSSI, and within the regions, they are allotted SFs corresponding to the proportions provided. The fairness of resource distribution is accomplished by the proposed power allocation scheme, which aims to optimise the RSSI of the end nodes, allocating low TP to the end nodes with a weak signal and high TP to end nodes with a weak signal. They achieve uniform DER for all the end nodes notwithstanding the distance from the gateway and maintain the end node’s lifespan by applying low TP levels reducing power consumption by twenty-two percent compared to standard ADR. The authors showed that by incrementing the number of end nodes in the network, the fairness index between end nodes decreases. This would favour communication from end nodes nearer to the gateway in comparison with those further away. This approach is therefore only feasible in extremely small networks whose end nodes are positioned near the gateway. Using different propagation models in the simulation is worth investigating.

A mathematical model whose numerical analysis results in a closed-form formula that maximises throughput whilst complying with transmission duty cycle (TDC) regulations was proposed in [107]. Their model mitigates against strict restrictions imposed on the duty cycle of ISM bands in some regions and improves transmission and power efficiency in the end nodes. The approach presents two meta-heuristics to solve an optimisation problem by computing the transmission policy. An optimal transmission policy means optimal selection of BW, SR, CR and TP. By considering band utilisation and power utilisation efficiency together, the highest achievable throughput of end nodes is calculated and optimised regarding a series of possible transmission parameters, hence achieving the optimal transmission policy. The authors resolve the convolution of LoRaWAN networks by modelling the core status of end nodes by applying the Markov model. In so doing, they develop a closed-form formula for node performance which is optimised mathematically with classic maximisation algorithms. This method increases performance by over thirty-three percent compared to the standard ADR scheme and is indicated to be able to operate in hardware-constrained IoT devices. The strength of this approach is that the model is based on an optimal policy derivation theory, which gives the approach the ability to statistically predict the performance of the end nodes in the LoRaWAN network. The drawback is that it is a complex combinatorial optimisation problem which cannot be solved directly. Future research could investigate the use of a simpler optimisation approach.

Reinforcement Learning (RL) based approach is used in [108] wherein they derive efficient ways of disseminating updated transmission configurations to maximise throughput while mitigating against TDC limitations. The authors mathematically model the average throughput per end node as a function of the packet generation behaviour of the end nodes such that the optimal transmission parameters are obtainable. They use the RL-based algorithm to update the configuration of individual end nodes to maximise the accumulated throughput per end node. They then analyse the behaviour of the LoRa nodes focusing on when and how packet collision may occur. Centred on this analysis, they mathematically depict the performance of LoRaWAN as a function of the transmission characteristics of the constituent nodes. The results show a significant improvement in throughput per node compared to the standard ADR algorithm. The strength of this approach is that it takes into consideration the fact that IoT networks are heterogeneous, that send packets at different packet rates and varying payloads. In the model, they consider randomly distributed end nodes and the capture effect. Instead of just maximising LoRa performance, they update transmission parameters of the overall network configurations. This approach improves throughput but does not look into its effect on power consumption. Further study on how this approach can be used to aggregate transmission settings from different gateways in a single updating packet in a LoRa system with multiple gateways is open for research. Channel attenuation and data collision are classified as reasons for packet loss in [109]. The authors formulated an ADR selection scheme with enhanced loss differentiation which selects a reasonable data rate that maximises throughput. The solution comprises three parts: prediction of channel attenuation, data collision probability and a data rate controller. They establish a channel attenuation model which they use to determine packet loss probability by channel attenuation. They then find the probability of data collision due to interference. A simulation model is established to investigate the correlation between the number of end nodes and the packet loss ratio (PLR) in the LoRa network using one gateway. They use MATLAB simulation to analyse and validate the performance of the technique. The proposed scheme showed reduced packet loss and improved DER compared to the standard ADR scheme and EXPLoRa. In this approach, the authors only considered a situation where the nodes report periodically. Future work could look at event-driven applications as a consideration.

A concept of network slicing was introduced in [110]. The LoRaWAN network is partitioned into several virtual networks, termed network slices, to efficiently assign network resources to support specific QoS requirements for every slice. Within IoT, every end node demands specific QoS requirements regarding delay and reliability determined by the type of IoT application being run. The authors use various network slicing strategies with different SF distributions to evaluate the network performance and optimise SF allocation for each slice. They proposition an adaptive dynamic inter-slicing algorithm wherein the BW is reserved on each LoRaWAN gateway using maximum likelihood estimation (MLE). They then improve that algorithm by considering each gateway individually, reserving its BW after utilising MLE on the end nodes within its range (intra-slicing algorithm). They compared the two adaptive dynamic slicing propositions to a standard fixed slicing strategy in which the gateway's BW is reserved uniformly among all the slices. Their results indicated an improvement in the optimisation of ADR due to an efficient coordination of resources. The strength of this approach is the provision of isolation of end nodes and its ability to maximise the efficiency of resource allocation in each LoRaWAN slice. The drawback is that energy consumption in the adaptive dynamic network slicing algorithm is increased compared to the static and dynamic configuration. The authors extended this work in [111] by taking into consideration some smart city applications representative of different QoS classifications and using a slice-based SF and TP configuration optimisation. They proposed a new slicing optimisation method called TOPG that was formulated on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Geometric Mean Method (GMM). Their suggested scheme sets the LoRa SF and TP parameters efficiently to improve the performance of every slice in terms of QoS, reliability and energy utilisation. The results showed that TOPG outperforms static and dynamic configuration strategies, highlighting its effectiveness in the provision of dynamic slice-based configurations and improving the performance of LoRa slices with regard to reliability and the percentage of end nodes that fulfilled their throughput and delay requirements.

The joint SF assignment and transmit power allocation algorithm has been investigated in [112]. They consider both co-SF and inter-SF interferences for the improvement of throughput fairness. In theory, there is a dramatic decrease in performance levels when orthogonality conditions are not met under the same SF conditions and communication channel. The authors formulated a joint SF and TP distribution problem to maximise the minimum UL throughput of end nodes dependent on co-SF and inter-SF interferences and power constraints. They based their strategy of SF allocation on the matching theory. Once the end nodes have been allocated SFs, optimisation of the power distribution parameters is performed so as to maximise the minimal throughput achieved on each SF. The authors addressed the intractability of the joint SF and power distribution problem by splitting it into two subproblems: SF allocation under fixed TP, and TP distribution under fixed SFs. They use both linear and quadratic approximation to make the non-linear inequalities in the feasibility problem tractable. Their simulation results showed that in spite of severe co-SF and inter-SF interferences, the propositioned algorithms outperform standard algorithms, jointly with regard to minimum end node data rates, user fairness, and average end node throughput. The two propositioned linear and quadratic approximation methods to tackle the non-linear feasibility problem for TP distribution produced efficient TP solutions, resulting in significant energy conservation, whilst further improving minimal throughput and user fairness.

### 2.5.3 Energy efficiency

Authors in [58] evaluated the performance of LoRaWAN under different scenarios using computer simulation and testbeds. They investigate the network performance regarding PDR, mean energy usage per transmission and mean energy utilisation due to packet collision per node. They show that the LoRa network performance is enormously reliant on the configuration of SF, CR, and BW. The experiments show the access strategy of pure Aloha has limitations which affect performance. The shortcoming could be mitigated by the randomisation of BW selection and node-specific optimisation to maximise data rate in relation to its channel conditions and contention severity. They conduct several experiments, the first which considers robustness and uplink data rate which they evaluate with and without the capture effect. In the second experiment, they incorporate multiple frequency randomisation to minimise the collisions. In this experiment, they adopted the slowest case from Experiment 1. The results show that the frequency randomisation that was introduced is capable of increasing the PDR of the slowest case. In the final experiment, they contrast two simple optimisations. The first optimisation, Opt1, sets the parameters in every end node so as to minimise ToA, which is determined by its distance from the gateway. The second optimisation, Opt2, sets the parameters in every end node so that it minimises its ToA and energy consumption. In other words, Opt2 attempts to minimise the energy utilisation of the solution attained by Opt1. The results show that optimisation can yield higher PDR and lower energy consumption. Interference from other ISM frequency users was not considered in this approach but could be a crucial factor which affects the performance. This could be interesting for future research. It could also be noteworthy to examine the effect of the different classes of the end nodes and their DL transmissions including the presence of multiple gateways in the vicinity.

In [113] the authors aim to optimally transmit data with a high PDR whilst maintaining a low energy utilisation. They introduce integer linear programming models to establish the optimum allocation of the parameters by considering the distribution of the end nodes and the impact of transmissions from the surrounding end nodes. They split the optimisation into two phases. First, they optimise the SF such that the collisions in the SF with the most traffic are marginal, and the collisions in every SF are balanced for all gateways to guarantee reliable communication within the network. As the problems in consideration are non-linear, they are converted into tractable integer linear programming models. Secondly, they optimise the TP to minimise the energy consumption in the network. After obtaining the optimum configuration, they analyse the solutions by means of extensive network simulations and compare them to different state-of-the-art algorithms. The results illustrate that the optimal configurations consistently perform better, achieving greater PDR and nominal energy utilisation across different scenarios. The approach can guarantee that a significant proportion of end nodes communicates reliably with a high PDR. All the network end nodes share the improved PDR thus guaranteeing an unbiased distribution of RF resources to all the end nodes. The strength of this approach is that the models are general, thus allowing network configuration with single or multiple gateways, along with different spatial configurations of LoRa devices. Commercially available solvers can be used to solve the optimisation model within a short space of time. This means that even for huge and dense networks with thousands of devices, the proposed model can be readily employed by service providers to establish the optimum setting of the LoRa parameters. The dynamic reconfiguration of the LoRa parameters could be an open area for research. More accurate path loss parameters could be estimated using linear regression on measured data instead of sourced data [100] used in the experiments. The deployment environment of the network highly affects the actual path loss parameters.

An ADR scheme that efficiently optimises the PER fairness within a LoRaWAN cell was developed in [114]. The authors achieved this by optimising the TP and SF for every end node whilst circumventing near-far problems by allotting outlying end nodes to different channels. End nodes are arranged by their path loss and divided into uniform clusters whose number is equivalent to the number of available channels. Every cluster is allocated a distinct channel and inside the clusters the proportion of end nodes employing the SFs is relative to $s/2^s$, corresponding to the solution of the optimisation problem to minimise the maximal collision probability among all the SFs. The algorithm calculates the optimal SF allocation to utilise in order to minimise the collision probability. The scheme optimally assigns SFs and distinct power levels to nodes within a LoRaWAN cell such that the signals do not interfere with each other. This scheme improves the PER for end nodes further from the gateway. Simulations of this approach implemented in ns-3 demonstrate that the PER can be reduced up to fifty percent for end nodes further away from the gateway in a moderate contention scenario. The overall network PER is reduced by 42%. The approach reduces operating expenditure by reducing energy consumption and providing wide network coverage which in turn reduces the number of gateways. The scheme uses a uniform distribution of the end nodes around the gateway and all the end nodes can use all SFs and TPs, that is, all end nodes in the network are capable of reaching the gateway with each SF and each TP configuration. This does not function in actual networks where specific end devices can only utilise a subset of the configuration parameters determined by the distance from the gateway. Further study could investigate randomly distributed end nodes. They consider unacknowledged traffic in this work.

Modulation and coding schemes (MCS) affect the transmission duration of the data frames. Data delivery time is dependent on network performance which impacts on energy consumption. For example, [25] considers failures in attempts to transmit triggered by arbitrary noise in the channel. The authors develop a precise analytical model of the data delivery time, dependent on the network setup. They show that their model can be used in the MCS (SF, BW, CR) election process to fulfil heterogeneous QoS requirements of different types of traffic. They presented a precise mathematical model of transmitting data which allows for estimating performance indices such as PLR payload and delivery time distribution. The strength of this approach is that it considers a heterogeneous network with various types of traffic and QoS requirements. Furthermore, the proposed model allocates MCSs such that QoS requirements are fulfilled. The algorithm has a drawback in that it does not consider inter-SF interference which is vital for huge network loads. The model can be improved to not only improve the packet loss ratio in the network but in addition the PLR distribution and to take into account the non-orthogonality of SFs in the model.

In [115] the authors develop an approach that improves QoS of LoRaWAN network by reducing data collisions and energy consumption and increasing DER. They use the Mixed Integer Linear Programming (MILP) optimisation method to generate optimum settings for SF and Carrier Frequency (CF) parameters. LoRaSim simulation is employed to demonstrate the effectiveness of the approach for different network scales. For their model, the authors assumed that BW and CR are fixed in computing ToA while they varied CF and SF to maximise the success probability. Three evaluation metrics were used to assess the network performance, namely, DER, number of collisions and network energy consumption. Simulation results demonstrated that MILP optimised the assignment of SF and CF pairs with over a six percent increase in DER compared to the standard LoRaWAN ADR and the number of collisions thirteen times smaller. The network energy consumption became almost three times lower than the equal-distribution and random dynamic allocation strategies. The strength of their approach is that it has backward compatibility with the standard ADR scheme, implying they are implementable in off-the-shelf LoRa devices. Future work could entail extending the optimisation approach to longer transmission distances and a bigger number of gateways.

The authors in [116] present a performance improvement technique through SF distributions for LoRa networks. They formulate the optimisation problem for the SF distribution to maximise the packet reception probability (PRP) under a constraint for the mean energy utilisation of each end node. This makes provision for the network performance to improve under the constraint for each end node by solving this optimisation problem. The authors develop a technique to solve the formulated problem based on a distributed genetic algorithm, which is a metaheuristics technique. The technique improves the network performance by assigning the SFs to end nodes under the constraint of the average energy consumption of each end node. The assumption is that the end nodes are static and their number in the network does not change. The PRP is derived while considering the imperfect orthogonality of the SF in LoRa networks. Their results showed that the PRP performance of their proposed technique is superior and uses less average energy utilisation for all end nodes compared to the existing schemes. Future work could involve energy consumption per node rather than an average for all the end nodes.

## 2.6 COMPARISON AND DISCUSSION OF OPTIMISED ADR SCHEMES

In this chapter, we performed a comprehensive analysis of solutions that have been developed to optimise ADR algorithms. The proposed optimisation techniques address specific challenges such as scalability [17, 33, 34, 98, 99, 101–103], throughput [32, 104–108, 110–112] and energy efficiency [25, 58, 100, 113–116]. Our analysis distinguished the approaches used and highlighted the challenges and performance in the studies considered. Table 3 shows a summary of the comparison of the reviewed literature. The analysis of the literature shows that existing ADR schemes use different algorithms with different computational complexities to optimise the data rate, depending on the different goals such as RSS, congestion, capture effect and channel contention. Computational complexity refers to the number of resources required to run the algorithm, particularly time and memory requirements expressed as a function n → f(n), where n is the size of the input and f(n) is the worst-case complexity or the average-case complexity. In [111] the adaptive slicing and SF-TP configuration algorithm has a constant complexity of $\mathcal{O}(1)$ for the static algorithm owing to its simplicity. However, the overall complexity of the proposed dynamic adaptive slicing and SF-TP algorithm and TOPG algorithm is $\mathcal{O}(n^2)$. Complexity is minimised in TOPG due to the server reducing the search space to SF values that acknowledge the guaranteed bit rate threshold. The computation time is reduced without a significant effect on QoS performance. In [112] the running time of the developed SF-Allocation algorithm is upper bounded by $\mathcal{O}(NM+Q^2+M^2)$. The complexity of the matching algorithm is not a constraint in an actual LoRaWAN because the algorithm operates on the NS whose computational capacity is expansive. In [114] the number of end nodes was capped at 1000 because of the restricted memory of the computer. All the transmission parameters needed to be broadcast to the end nodes resulting in a $\mathcal{O}(n^2)$ memory consumption. In [115] the Approximation Algorithm maintains a linear complexity time $\mathcal{O}(n) = 111n + 57$ in the worst-case. The algorithm is designed to function in the LoRaWAN Application Layer and end nodes with a time complexity that is equivalent to the ADR scheme, so that the proposed optimisation algorithm does not cause any substantial computation overhead, neither in the end nodes nor in the NS. Generally, the operation of the algorithm uses less than 20 kB of memory, 4 kB on average and 20 kB being the worst-case, This is insignificant since most commercial off-the-shelf end nodes contain not less than 128kB of flash memory [117].

The algorithms used to improve scalability in LoRaWAN were discussed in [17,33,34,98,99,101–103]. The strength of the approach in [33] is that it considers the level of congestion in the network, unlike the legacy ADR scheme. The drawback of this approach is that the process demands an ACK DL message for each transmission. Although the proposed algorithm in [34] shows a significant increase in reliability and scalability, there is a drawback. Waiting for twenty frames in order to adjust the scheme may be too long. For dense networks, link-based adaptation is inadequate. Future work could consider incorporating collision probability and the distribution of parameters in the network. Balancing the link budget for every link and PDR of the entire network could further improve scalability. In [17] although the light-scheduling approach improves reliability and scalability, there is an introduction of additional energy consumption as the end nodes need to listen for the beacon from the gateway before sending a packet. The approach does not eliminate packet collisions entirely because uplink messages could still collide with beacons from other gateways. Because the approach uses Aloha, it also means collisions cannot be eliminated. The proposed algorithm in [98] reduces the number of data messages in the UL as well as the MAC command messages in the DL and achieves superior error performance in poor-condition channels. This enables the extension of the network range. The drawback of this algorithm is that the simulation model used does not consider large complex networks. The use of a Tree-Based SF Clustering Algorithm (TSCA) which allocates nodes to numerous subnets in [103] vastly improves scalability as is the characteristic of mesh networks. In our opinion, the algorithm in [102] is the best approach in improving scalability as the proposed solution outperforms the equal-interval and equal-area-based SF distribution schemes in terms of average network PSP.

ADR schemes that maximise throughput maximising solutions for the ADR scheme were discussed in [32, 104–108, 110–112]. The ordered waterfalling technique is used in [104] for even distribution of channel load between the end nodes in the system by equally distributing SFs and then channel utilisation. This algorithm is designed under the assumption that end nodes transmit with a uniform data rate and payload which is not practical. When we compare it to [32] which uses the gradient projection method we find that their approach also uses the load balancing approach but factors in the contention issue in optimising ADR making it a better scheme in maximising throughput. The algorithm in [106] uses all four transmission parameters to maximise DER and attempts to fairly allocate data rates. The algorithm works with nodes close to the gateway, making the solution suitable only for small networks. The algorithm in [108] takes into consideration the fact that IoT networks are heterogeneous and send packets at different packet rates and varying payloads. In the model, they consider randomly distributed end nodes and the capture effect. Instead of just maximising LoRa performance, they update transmission parameters of the overall network configurations. Network slicing brings an interesting dimension to ADR optimisation which sets the LoRa SF and TP parameters efficiently to improve the performance of every slice in terms of QoS. In our opinion the algorithm in [112] provides the best approach for maximising throughput outperforming standard algorithms, jointly with regards to minimum end node data rates, user fairness, and average end node throughput. The challenge of conserving energy in LoRaWAN networks is a QoS in the ADR algorithms in [25, 58, 100, 113–116]. In [58] they first optimise every end node to minimise ToA, which is determined by its distance from the gateway, searching for optimal gateway location ensuring all nodes are connected. They then use the results of the first optimisation to do a second optimisation that minimises energy consumption. Although the results show that optimisation can yield higher PDR and lower energy consumption, interference from other ISM frequency users was not considered in this approach yet it could be a crucial factor which affects the performance. In [113] they also optimise two parameters, first they optimise SF allocation to ensure reliable communication and then optimise TP to minimise energy consumption in the network. The approach guarantees that a significant proportion of end nodes communicates reliably with a high PDR. All the network end nodes share the improved PDR thus guaranteeing an unbiased distribution of RF resources to all the end nodes. It is a better approach compared to [58] because the models are general, thus allowing network configuration with single or multiple gateways, along with different spatial configurations of LoRa end nodes. It is a more practical approach. In [114] the scheme uses the uniform distribution of the end nodes around the gateway and all the end nodes can use all SFs and TPs, that is, all end nodes in the network are capable of reaching the gateway with each SF and each TP configuration. This does not function in actual networks where specific end devices can only utilise a subset of the configuration parameters determined by the distance from the gateway. In [25] they use an optimisation approach with three transmission parameters, SF, TP and CR to develop an analytical model for a heterogeneous network with various types of traffic and QoS requirements. The algorithm has a drawback in that it does not consider inter-SF interference which is vital for huge network loads. The model can be enhanced to improve the packet loss ratio in the network and energy consumption. In [115] they optimise the ADR scheme using SF and CF to maximise the success probability while fixing BW and CR to compute ToA, improving the DER, thus conserving energy. Out of all these schemes whose objective is energy efficiency, the most promising solution in our opinion, is [116] The technique improves the network performance by assigning the SFs to end nodes under the constraint of the average energy consumption of each end node.

The study of ADR in LoRaWAN networks reveals that common objectives for the proposed algorithms are scalability, throughput, and energy efficiency. Testbeds, simulations, and mathematical models are employed to develop and evaluate ADR algorithms and schemes. The mathematical models use machine learning and mathematical optimisation to optimise the ADR schemes. Various ADR algorithms draw in different metrics that influence the standard transmission parameters where others consider coverage, channel access/contention, RSS, PDR and so on, as shown in Table 2.4. There are trade-offs between achieving high data rates or energy consumption and the performance metrics required. Many schemes use a single gateway in their proposed solutions as it is a simple and straightforward network. Most of the literature reviewed evaluated their ADR schemes using simulation tools such as NS-3, MATLAB, OMNET++, FLoRa and LoRaSim. The algorithms are mostly simulation-based as testbeds prove to be very expensive.

**Table 2.4.** Comparison of adaptive data rate techniques.

| **Ref** | **Objective** | **Optimisation approach** | **TB** | **Simulation** | **Mathematical model** | **CH** | **RSS** | **PDR** | **CV** | **CC** |
|---|---|---|---|---|---|---|---|---|---|---|
| [58] | Energy efficiency | Machine learning | ✓ | ✓ | | ✓ | | ✓ | | |
| [33] | Scalability | Machine learning | ✓ | ✓ | Logistic regression | ✓ | | | ✓ | |
| [34] | Scalability | | | F. OMNeT++ | | | ✓ | ✓ | | |
| [17] | Scalability | Coarse-grained scheduling | | | Light-weight scheduling | ✓ | | | | |
| [98] | Scalability | Machine learning | | MATLAB | Variable hysterisis | ✓ | ✓ | ✓ | | |
| [99] | Scalability | | | | Integer linear programming | ✓ | | ✓ | ✓ | |
| [100] | Scalability | | | NS-3 | | | | | | |
| [101] | Scalability | Mathematical optimisation | | Monte Carlo | Stochastic geometry | ✓ | | | ✓ | |
| [102] | Scalability | | ✓ | ✓ | | | | | ✓ | |
| [103] | Throughput | Waterfalling technique | | | | ✓ | ✓ | ✓ | ✓ | |
| [104] | Throughput | Constrained optimisation | | | Gradient progression method | ✓ | | | | |

**Table 2.3.** Comparison of adaptive data rate techniques (continued from the previous page).

| Ref | Objective | Optimisation approach | TB | Simulation | Mathematical model | CH | RSS | PDR | CV | CC |
|---|---|---|---|---|---|---|---|---|---|---|
| [32] | Throughput | | | LoRaSim | | | ✓ | | | |
| [105] | Throughput | Mathematical optimisation | ✓ | ✓ | Markov-meta heuristic | | | | | |
| [106] | Throughput | Machine learning | | | Reinforcement learning | ✓ | | | | |
| [107] | Throughput | | | MATLAB | | ✓ | | ✓ | | |
| [110] | Throughput | Machine learning | | NS-3 | Maximum likelihood estimation | | ✓ | | ✓ | ✓ |
| [111] | Throughput | Mathematical optimisation | | MATLAB | Linear & quadratic approximation | | ✓ | | | ✓ |
| [112] | Energy efficiency | | | F. OMNeT++ | Integer linear programming | | | | | |
| [114] | Energy efficiency | Constrained optimisation | | NS-3 | Genetic algorithm | ✓ | | | ✓ | ✓ |
| [25] | Energy efficiency | | | ✓ | ✓ | ✓ | | | | |
| [115] | Energy efficiency | Mathematical optimisation | | LoRaSiM | Mixed integer linear programming | ✓ | | ✓ | | ✓ |
| [116] | Energy efficiency | Constrained optimisation | | MATLAB | Distributed genetic algorithm | ✓ | | ✓ | | |

## 2.7 CHALLENGES AND FUTURE DIRECTION

The research conducted showed that the ADR algorithms that have been analysed prioritise different performance metrics and hence provide various solutions. Data packet collision and transmission duty cycle are issues that are common in many of the ADR schemes. Most approaches implement their ADR schemes using a single gateway. Research gaps and future work that were identified in the literature reviewed are as follows:

### 2.7.1 Machine learning

In the solutions that use machine learning, the NS performs the learning and delivers the results to the end nodes to predict some metric being monitored, for instance, network congestion, using centralised machine learning. This approach centralises the training data on one machine, the NS. This can create a bottleneck in collecting training data. Future work may include using distributed learning of the nodes rather than centralised learning. Distributed machine learning enables end nodes to collaboratively learn the prediction model whilst keeping all the training data on the end node and reducing learning errors. Future work could also include the use of different optimisation methods for predicting the network metric under scrutiny.

### 2.7.2 Transmission policy

Because of its implementation in the ISM license-free frequency band, LoRa deployments are bound by strict legal protocols, especially where no listen-before-talk schemes are utilised. ISM bands are regulated by the TDC to determine the maximum time the band can be occupied per hour. For example, in Europe, the ETSI TR 103 526 documents rule that, for the 868.0–868.8MHz band, the maximum allowable TDC is one percent. This implies that IoT devices may not occupy the ISM band for more than thirty-six seconds per hour, prohibiting the transmission of new packets when this limit is attained. Schemes that mitigate against strict restrictions imposed on the duty cycle of ISM bands are an open area for research.

### 2.7.3 Perfect orthogonality

LoRa uses orthogonal SFs. These allow the network to preserve the battery life of the end nodes linked to the network by adaptive optimisation of each end node's power setting and data rate. Many ADR algorithms assume perfect orthogonality and do not consider inter-SF interference which is vital for huge network loads. Inter-SF interference decreases network performance considerably, especially for high SFs where packets have a higher ToA. The models can be improved to not only improve the packet loss ratio in the network but in addition the PLR distribution and to take into account the non-orthogonality of SFs in the model.

### 2.7.4 Homogenous end nodes

The majority of proposed ADR schemes consider homogenous end devices which transmit fixed payloads. In actual deployments, IoT networks are heterogenous, that send packets at different packet rates and varying payloads. Further study can include implementing ADR schemes in networks that are heterogeneous and determining the power consumption in such networks.

### 2.7.5 Mathematical models

Mathematical models are common in optimising ADR schemes. The models help in studying the different metrics, predicting the behaviour and then solving the optimisation problem. The models can solve the problem of collision and duty cycle limitations for example. However, most models consider simple single gateway networks and do not support implementation with multiple gateways. Future work would entail optimising the placement of the multiple gateways and incorporating large complex networks in the models. Additionally, some models use complex combinatorial optimisation problems which cannot be solved directly. Future work would be to find simpler optimisation methods.

### 2.7.6 Uniform distribution of end nodes

The assumption that an ADR scheme uses uniform distribution of the end nodes around the gateway and that all the end nodes can use all SFs and TPs suggests that all end nodes in the network are capable of reaching the gateway with every SF and every TP setting. This does not function in actual networks where specific end devices can only utilise a subset of the configuration parameters determined by the distance to the gateway. Further study could investigate randomly distributed end nodes.

Different optimisation models are implemented in the ADR schemes. Where machine learning algorithms are utilised, one could use fuzzy logic or mathematical optimisation and vice versa. Algorithms that consider network congestion, packet collision probabilities, and the use of multiple gateways could improve ADR. Different propagation models, randomly distributed end nodes, packet loss ratio and non-orthogonality of SFs are issues to be considered in the models to improve performance.

## 2.8 CHAPTER SUMMARY

This chapter introduced the Internet of Things and its common technologies. An overview of LoRaWAN describing its features and building blocks ensued. The applications of LoRaWAN were presented and the impact of multiple gateways on the network performance was discussed. The focus narrowed to the adaptive data rate scheme, an essential feature of LoRaWAN. The chapter reviewed the ADR schemes that have been proposed in the public domain and classified the solutions. We discussed the impact of the ADR solutions on the performance of LoRaWAN networks. There are numerous ADR schemes that have been proposed in literature that use different techniques to accomplish desired optimisation goals depending on the objective of the scheme responding to specific performance needs and applications. The literature study revealed that although the transmission parameters are standard, the methods and considerations for ADR to improve network performance are countless. Based on the review, we identified the gaps in the literature and proposed future work on ADR optimisation. Although existing solutions achieved promising performances, they are not optimal therefore it is essential to find efficient solutions. To this end, ADR algorithms can be improved to increase the energy efficiency and performance of energy-constrained end nodes, which forms the basis of the investigations carried out in the following chapters of this thesis.

# CHAPTER 3 A FUZZY-LOGIC BASED ADR SCHEME

## 3.1 CHAPTER OVERVIEW

Long Range Wide Area Network (LoRaWAN) technology is rapidly expanding as a technology with long-distance connectivity, low power consumption, low data rates and a large number of end devices (EDs) that connect to the Internet of Things (IoT) network. Due to the heterogeneity of several applications with varying Quality of Service (QoS) requirements, energy is expended as the EDs communicate with applications. The LoRaWAN Adaptive Data Rate (ADR) manages the resource allocation to optimise energy efficiency. The performance of the ADR algorithm gradually deteriorates in dense networks and efforts have been made in various studies to improve the algorithm's performance. As presented in Chapter 2, there is a need for more efficient solutions to resource allocation. Chapter 3 delves into the system model of the proposed fuzzy logic-based approach, aligning with the identified research gap. The chapter provides a comprehensive exploration and presentation of the fuzzy-logic-based adaptive data rate system model. The system model and analysis discussed in this chapter have been published in a journal article entitled "A Fuzzy-Logic Based Adaptive Data Rate Scheme for Energy-Efficient LoRaWAN Communication" [94]. This publication serves as a valuable addition to the existing body of knowledge.

This chapter is structured as follows: Section 3.2 introduces LoRaWAN. Section 3.3 presents related work on the LoRaWAN technology. Section 3.4 focuses on the adaptive data rate mechanism of LoRaWAN and the fuzzy logic concept. Section 3.5 presents the different tools used to implement the proposed algorithm. Section 3.6 describes the proposed model of the ADR scheme, configuration details and simulation parameters. Section 3.7 provides the performance analysis and discussion of the results. Finally, Section 3.8 provides a summary of the chapter.

## 3.2 HARNESSING LORAWAN

LoRaWAN is a proprietary trademark synonymous with LoRa and a member of the Low Power Wide Area Networks (LPWANs) technology on the Internet of Things (IoTs). It connects numerous end devices (EDs) with low-cost, low-data-rate, long-range, and long-lasting batteries suitable for various IoT applications with varying QoS in various industries such as smart agriculture, smart metering, smart cities and smart healthcare [7–9, 118]. Unlike NBIoT [119] and Sigfox [5], which are proprietary, LoRaWAN operates in the industrial, scientific and medical (ISM) band. LoRa employs a physical (PHY) layer chirp spread spectrum (CSS) modulation technology which provides the highest receiver sensitivity while consuming the least power in comparison with other LPWAN technologies [120]. The CSS enables the demodulation of data packets with low signal-to-noise ratio (SNR) at lower data rates. EDs sense the environment and communicate with the network server (NS) via the gateway (GW). Depending on the distance from the gateway and the propagation conditions, transmission parameters are set, namely, spreading factor (SF), transmission power (TP), bandwidth (BW) and coding rate (CR). These transmission parameters have an impact on energy consumption.

LoRaWAN employs the Adaptive Data Rate scheme, an essential element which regulates these transmission parameters, to optimise resource allocation. The key objective of the ADR scheme is network optimisation for maximum capacity, ensuring that EDs always transmit with optimal transmission parameters. Since the lifespan of the ED's battery is limited, charging or replacing batteries may be impossible in some harsh environments; thus, energy efficiency is considered to avoid network lifetime degradation in a LoRaWAN network. Numerous works on ADR either optimise the spreading factor to improve packet success ratio using a channel-adaptive SF recovery algorithm [121], packet reception probability (PRP) under average energy consumption constraint [116] using a distributed genetic algorithm, maximise the throughput of the EDs using the matching theory [122], or optimise the transmission power to maximise utility [92]. Other approaches use optimisation of the ADR mechanism's convergence time [123], which is hampered by a high spreading factor and does not correlate to efficient energy consumption.

In this chapter, a fuzzy-logic-based adaptive data rate algorithm is proposed to improve energy consumption in a LoRaWAN network. The proposed scheme makes use of the Mamdani fuzzy inference system (FIS) to create an inference system for selecting network parameters to achieve high network efficiency for various IoT scenarios using LoRa networks. The proposed scheme aids in the decision-making process by selecting optimal SF and TP parameters based on channel estimates derived from the signal-to-noise-ratio (SNR) of the four most recently received data packets, which reduces computational costs when compared to traditional ADR, which considers 20 data packets. To the best of our knowledge, no research has considered improving ADR by optimising the SF and TP using fuzzy logic. Adapting fuzzy logic to changing ADR requirements will improve energy efficiency. The main challenge is how to implement the FL-ADR algorithm to configure the transmission parameters to provide reliable communication while using as little energy as possible. Our proposed scheme makes use of the LoRaWAN module developed in [124], which is built under the ns-3 simulation module. The ns-3 is an open-source discrete event simulator written in C++ and Python that simulates simple and complex network systems. The LoRaWAN module complies with the class A LoRaWAN 1.0 specifications [125]. This chapter makes the following contribution:

1. We improved Semtech's traditional ADR to obtain $\text{SNR}_{\text{margin}}$ allocation by calculating the SNR average of four (4) packets rather than the traditional ADR's twenty (20) packets, which reduce the computational cost of searching for the $\text{SNR}_{\text{margin}}$ in every frame transmitted.
2. We developed a fuzzy-logic-based algorithm to calculate the optimal SF and TP values using the obtained $\text{SNR}_{\text{margin}}$ for the EDs to select an efficient data rate to be transmitted.
3. We evaluated the performance of the system through extensive simulations. We used six metrics to compare the results obtained with the traditional ADR and the ns-3 ADR scheme, namely, Total Energy Consumption (ET), Confirmed Packet Success Rate (CPSR), Uplink Packet Delivery Ratio (UL-PDR), Interference/Collision Rate ($\text{I}_{\text{PR}}$), Lost-Because-Busy Rate ($\text{L}_{\text{PR}}$) and Energy Efficiency.

## 3.3 RELATED WORK

LoRaWAN networks have been implemented in numerous deployments and are rapidly growing due to the rising demand of smart applications in IoTs. The most ubiquitous challenge that exists regarding these deployments is energy efficiency [126]. The early ADR algorithms [31–33] sought to solve the challenge of scalability, congestion, throughput and packet delivery ratio without focusing on the schemes' impact on energy consumption. The authors in [104] propositioned two ADR methods of cumulative complexity: EXPLoRa-SF and EXPLoRa-AT to decrease collisions, enhance data extraction rate, and therefore improve network throughput. They, however, did not consider the effect of the algorithm on energy efficiency.

In Ref [127], dynamic LoRa (DyLoRa) was proposed, a scheme that uses a symbol error rate model to determine an energy-efficient SF and TP allocation. Optimising convergence time of the ADR mechanism is used in [123], channel allocation conditions in [128], frequency estimation in [129] and link level performance in [92], to formulate the problems that the ADR algorithms attempt to address. In Ref [130], the authors developed EARN, an enhanced greedy ADR mechanism with code rate modification to exploit adaptive $\text{SNR}_{\text{margin}}$ to mitigate the dynamic link changes. A spreading factor assignment strategy was introduced in [131] to evaluate the capacity vs. coverage trade-off in LoRaWAN. They define and compare the performance of nine assignment strategies using vector assignment. They provide evaluation results related to the proposed work. The adaptation of fuzzy logic in IoT to improve the efficiency of smart applications has gained attention [132, 133]. The fuzzy logic approach was used in [134] to predict efficient LoRa communication. They develop a fuzzy logic model to predict a high network efficiency under different environment scenarios. This work considers only the spreading factors of 7 and 9. Our proposed work builds on this previous research in [34, 134] to adapt fuzzy logic to the ADR scheme by optimising SF and TP to provide efficient energy usage that improves LoRaWAN communication. In contrast to the traditional ADR scheme, the ADR+ scheme developed in [34] outperforms the traditional ADR scheme with the use of the 20 measured packets' average SNR instead of the traditional maximum SNR value. This resulted in improved energy efficiency. We propose a modification of the number of measured packets, the use of the packets' average SNR, and the development of a fuzzy logic-based algorithm to optimise the spreading factor and transmission power. This results in a reduction in energy consumption, hence prolonging the battery lifetime of the EDs. The key research papers discussed in this section are summarised in Table 3.1. The table highlights the shared characteristics in the cited papers.

**Table 3.1.** Summary of related work.

| Ref | Scheme | Objective | Metrics |
|---|---|---|---|
| [20] | State-space model | Congestion | Interference |
| [21] | Gradient Projection | Throughput | Channel contention |
| [22] | Logistic Regression | Congestion | Transmission delay, received signal strength |
| [23] | ADR+ | Link level performance, E.E. | PDR |
| [86] | EXPLORA | Throughput | Channel contention, coverage, data extraction rate |
| [111] | DyLoRa | Energy Efficiency | Symbol error rate, PDR |
| [112] | Efficient Channel Allocation Algorithm (ECAA) | Throughput | Channel contention |
| [113] | AdapLoRa | Frequency estimation, E.E. | Network lifetime, residual network energy |
| [74] | BE-LoRa | Link level performance, E.E. | PDR, packet success rate |
| [114] | EARN | Code rate modification, E.E. | Collision probability |
| Proposed | FL-ADR | Energy efficiency | PDR, CPSR, collision rate |

## 3.4 TECHNOLOGICAL OVERVIEW

Out of the OSI layer protocol, LoRaWAN utilises three layers of the protocol stack, namely, the PHY layer, MAC layer and Application layer. The PHY layer is represented by LoRa, a patented technology advanced by Semtech [56]. LoRa works in different frequency bandwidths depending on the regional parameters as prescribed in [26]. The characteristics of LoRa, for instance, topology, data transmission, error correction, modulation and data range, are described in [6]. The MAC layer is represented by

LoRaWAN, an open-source protocol managed by the LoRa Alliance. It is the interface between LoRa and the gateway by providing channel access, ADR control and security services. LoRaWAN is derived from pure ALOHA medium access, meaning that EDs do not check for channel availability before transmitting data packets, opening up to the possibility of packet collision. The LoRaWAN standard defines three device classes that support bidirectional communication, trading off performance for power consumption.

Depending on the application framework, LoRaWAN EDs could be modelled into three distinctive classes: Class A EDs are required to avail one or two receive windows after every UL transmission to permit the NS to distribute a prospective data packet to the ED. When an ED receives a DL transmitted in the initial window, it is exempted from unlocking the second window; otherwise, it should unlock the second window. Class B EDs are an extension of Class A behaviour with the addition of slotted receive windows for DL transmissions. Synchronisation of the receive window is done by means of a beacon packet transmission using the GWs. Class C EDs are also an extension of Class A behaviour by maintaining the receive window open at all times except during UL transmission. This provides Class C EDs with low latency DL transmission, which entails greater energy utilisation. This study only considers Class A EDs because ns-3 currently only implements Class A devices and Class A behaviour results in the least energy utilisation.

### 3.4.1 LoRaWAN adaptive data rate

The standard LoRaWAN ADR (which we will call Semtech-ADR to distinguish it from other ADR schemes used in this work) algorithm dynamically modifies the transmission parameters to extend the battery life and maximise throughput. The data rates and transmission power for every ED in the LoRaWAN network are adjusted to achieve this. The ADR algorithm is applicable on the ED side and the NS side. Data rate selection is determined by the transmission parameters and past performance of each ED. Battery lifetime is extended, and the global network capacity is increased by optimising data rates, time on air (ToA), and energy depletion, thereby enhancing the lifecycle of the end devices. Following the LoRaWAN Regional Parameters and Specifications [40, 41], EDs are required to accommodate specified data rates, further complicating the power constraint problem since SNR figures must range across specific thresholds and power levels. Given that the EDs should respond to the network's channel conditions, it is necessary that they have the capability to adjust the data rates and TP appropriately. A review of the LoRaWAN ADR framework is provided in [29].

To obtain optimal data rates, EDs must follow specific procedures [41]. Firstly, the end node selects the ADR bit in a UL message header requesting that the NS manage data rate adaptation. Subsequently, the NS sends LinkADRReq MAC instruction to the ED, which specifies the modification of its SF and TP, which results in a change in data rate. The ED uses the LinkADRAns MAC command settings to confirm the required settings to the NS. If the ED is unable to receive a DL message within the ADR_ACK_LIMIT while the current data rate is greater than the nominal data rate, all subsequent uplinks will be transmitted with the ADRACKReq bit set. If the ED is unable to receive a DL message within the ADR_ACK_DELAY from the NS, in the subsequent uplinks, the ED attempts to re-establish communication by changing to the next lower data rate which delivers an extended communication range. As a result, the ED reduces the data rate by a step each instance that the ADR_ACK_DELAY is attained. When the ED receives a DL message from the NS, it uses its internal counter ADR_ACK_CNT which is reset. Figure 3.1 details the ADR system flow effected at the ED.

On the network server side, the NS monitors the uplink quality and commands the EDs to adjust the SF and TP. The UL quality of each packet transmitted by the ED is recorded in the network server's history and compared to the minimum required SNR threshold. If the SNR of recent packets is found to be better, the NS commands the EDs to reduce SF and TP and vice versa. The main difference between the Semtech-ADR model and the ns-3-ADR implementation is that ns-3 does not use the 10 dB deviceMargin in its implementation. Another differentiating factor is that TP is adjusted in steps of 2 instead of 3 as implemented in the Semtech-ADR. The LoRaWAN network does not operate in stable network conditions due to varying weather conditions, radio interference, moving obstacles, and so on. These factors result in a constant change in the received signal strength indicator. It is imperative that there is no overestimation of the link. We therefore cannot have a crisp value for the target SNR_margin, necessitating the use of fuzzy logic to optimise transmission parameter resource management. The SNR_margin is used to estimate how much we can adjust the data rate by optimising SF and TP, which will result in minimised energy consumption.

### 3.4.2 Fuzzy logic system

We can define fuzzy logic systems (FLS) as universal approximators of nonlinear systems that perform the nonlinear mapping of an input data set to a scalar output data [135, 136]. We use FLS for decision-making based on "uncertain, imprecise environments" [137]. Fuzzy Logic Control-based systems do not process assumptions on the basis of the probability distribution framework. Because they can estimate any real continuous function to a compact set, FLS is specifically applicable to dynamic systems and can approximate these dynamic systems to any level of precision. An FLS consists of four core elements: the fuzzifier, the rules, the inference engine, and the defuzzifier [138] as illustrated in Figure 3.1. The fuzzification state transforms the crisp values of the system inputs into fuzzy values. This stage consists of computing the fuzzy values of the linguistic variables given their respective system inputs. The appropriate fuzzy rules are activated by utilising the fuzzy input values in the inference step, which then produce the commensurate fuzzy output values. In the final stage, the fuzzy output values are converted into crisp values at the defuzzification stage.

The fuzzy controller derives its output from the fuzzification of both inputs and outputs with the use of associated membership functions. Based on the value of the crisp input, the fuzzy controller will convert it to a range of inputs (members) of the associated membership functions. A membership function is a curve that expresses how every element in the input range maps to a degree of membership ranging from 0 and 1. The general types of membership functions are triangular, trapezoidal and Gaussian. The fuzzy inference process uses three methods that are proposed in literature, namely Mamdani, Sugeno and Tsukamoto [139]. The fuzzy logic algorithm is a problem-solving algorithm that uses the basic IF-THEN rule structure.

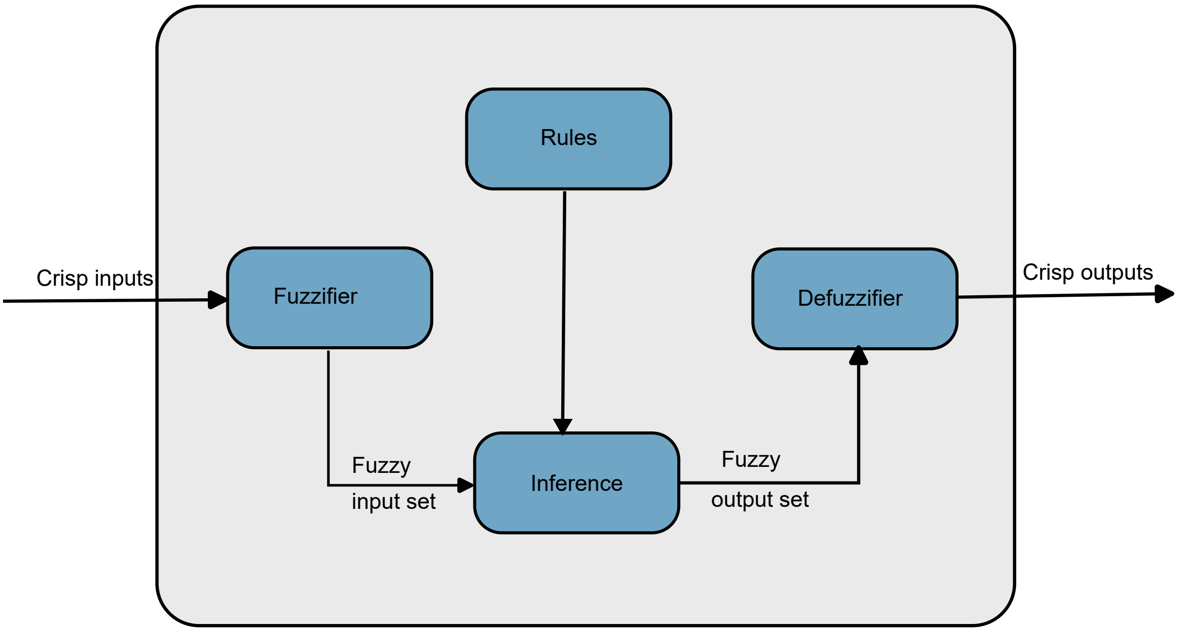


**Figure 3.1.** A typical fuzzy logic system.

## 3.5 IMPLEMENTATION TOOLS

Testing and researching real LoRaWAN systems presents several challenges. LoRaWAN networks are often owned and operated by specific organisations or service providers, and obtaining permission to conduct experiments on these networks may require negotiations, agreements, and sometimes financial arrangements which are difficult to obtain. In real LoRaWAN systems, network parameters such as transmission power, spreading factor, and data rates are often controlled by the network operator. Researchers may not have direct control over these parameters, which can limit their ability to conduct specific experiments or evaluate the impact of certain network configurations. Real LoRaWAN networks can have limitations in terms of scalability and available resources. Conducting large-scale experiments involving a high number of nodes or testing resource-intensive algorithms may not be feasible due to hardware limitations, energy constraints, or financial considerations.

To overcome these challenges, we resorted to utilising simulation tools to deploy and evaluate our own LoRaWAN network. Simulation tools enable rapid prototyping and testing of network configurations and protocols. Changes can be made quickly, and different scenarios can be tested efficiently. This accelerates the development process, allowing for faster iterations and optimisation. We reviewed the available LoRaWAN simulators in the literature, such as [30, 140, 141] and settled on a simulation tool that is open-source, that accurately models the behaviour of LoRaWAN networks including factors like signal propagation, interference, collisions, data rates, and network congestion. We looked for features that enable easy customisation of network topology and node behaviours, allowing modification of various parameters like transmission power, spreading factor, data rates, and network configurations. Ns-3 simulation tool was selected as the simulation platform for the implementation. However, within ns-3, a number of modules were implemented, such as [90, 142–144]. Out of these the LoRaWAN module by [90] available on [145] was selected due to the availability of a supportive community, user forums, and documentation associated with the simulator. The frequent updates, ongoing maintenance, and bug fixes provided by the simulator’s developers ensure compatibility with new protocol versions and improvements in simulation capabilities, making it a suitable choice.

In this work, we implemented the ns-3.36 version. The version of the “LoRaWAN module” implemented is v0.3.0 of 4 May 2021 commit 159cc5e. For fuzzy logic control, we used the FuzzyLite Libraries version 6.0 to facilitate the design and optimise the operation of fuzzy logic controllers using an object-oriented programming model, without the need for external libraries. Simulations are executed through a unified C++ script. This script serves the purpose of defining and configuring the simulation scenario, as well as handling all device configurations. Additionally, it carries out the simulation process and stores any resulting outputs in designated files. Configuration options can be defined either in the file or provided as command-line arguments. These arguments are then parsed to assign values to local and global variables, depending on the specified options. The management of simulations is accomplished through the utilisation of Simulation Execution Manager (SEM), a Python-based simulation manager. SEM facilitates this process by establishing a simulation campaign, which encompasses a comprehensive database of all executed simulations. This database includes the associated script and the corresponding values employed for each parameter. Instead of manually performing these actions for each simulation, one can easily specify all combinations of parameters through a Python script, streamlining the simulation process and facilitating more comprehensive experimentation.

The Mamdani fuzzy inference system was used to choose the parameters for the fuzzy logic implementation. This is because the Mamdani fuzzy inference system works well for our fuzzy logic control applications, where the linguistic variables and fuzzy rules model our system's nonlinear relationships between inputs and outputs. The rules in a Mamdani system are expressed in the form of "IF-THEN" statements, making it intuitive for us to define the behaviour of the system based on domain knowledge. Mamdani fuzzy inference system systems have been extensively studied and used in various fields since their introduction in the 1970s [146]. As a result, there is a wealth of literature, tools, and software libraries available for designing, implementing, and analyzing Mamdani systems. Triangular membership functions were employed in this work over the others, such as Gaussian, trapezoidal and bell, because of their simplicity, computational efficiency, and robustness. Triangular membership functions are simple to define and understand, they are characterised by just three parameters. The membership functions require minimal computational power to evaluate, given our resource-constrained network. They correspond intuitively to the gradual transition between non-membership (0) and full membership (1). in the fuzzy set. For the requirements of our application, triangular membership functions were the best fit.

### 3.5.1 System performance parameters

The parameters that were considered to measure the performance of our proposed adaptive data rate algorithm are Confirmed Packet Success Rate (CPSR), Uplink Packet Delivery Ratio (UL-PDR), Interference/Collision Rate ($I_{PR}$), Lost-Because-Busy Rate ($L_{PR}$), Total Energy Consumption (ET), and Energy Efficiency.

#### 3.5.1.1 Confirmed packet success rate (CPSR)

Confirmed packet success rate refers to the rate at which confirmed uplink packets are successfully received and acknowledged by the network server. It is the probability of successfully receiving the confirmed UL packet and its corresponding DL packet received in one of the available transmission attempts and is defined in (3.1).

$$PSR = \frac{DL_r}{UL_s}, \tag{3.1}$$

where $UL_s$ is the uplink data packets sent, $DL_r$ is the downlink packets successfully received at ED for at least one corresponding $UL_s$ packet sent over the uplink.

#### 3.5.1.2 Uplink packet delivery ratio (UL-PDR)

Uplink packet delivery ratio refers to the ratio of successfully received uplink packets to the total number of attempted uplink packets transmitted in a network as presented in (3.2). It is the probability that an ($\mathrm{UL_s}$) packet is correctly received whether or not the ACK is requested. It provides a measure of the reliability of packet transmission from end devices network server:

$$UL-PDR = \frac{UL_r}{UL_s} \tag{3.2}$$

#### 3.5.1.3 Interference/collision rate ($I_{PR}$)

Packet loss due to interference ($I_R$) means the GW successfully locks on the packet, but its reception is unsuccessful due to interference caused by the presence of overlapping packets. These interfering packets possess sufficient power to disrupt the orthogonality of the signals. We define the interference or collision rate ($I_{PR}$) as the ratio of the total received packets and the packets lost due to interference as defined in (3.3):

$$I_{PR} = \frac{I_R}{UL_s} \tag{3.3}$$

#### 3.5.1.4 Lost-because-busy rate ($\mathbf{L_{PR}}$)

Packet loss due to GW transmission ($\mathrm{I_R}$) is the disruption of packet reception caused by the transmission of a DL packet which may already be in progress at the time of the packet's arrival, or may begin while the packet is still being received, in the instance where the GW prioritises transmission. We define the lost-because-busy rate ($L_{PR}$) as the ratio of the total received packets and the packets lost due to GW busy:

$$L_{PR} = \frac{L_R}{UL_s} \tag{3.4}$$

#### 3.5.1.5 Energy efficiency

Energy efficiency (EE) provides insights into how effectively the network utilises energy resources. To calculate the energy efficiency of the ADR algorithms, the energy consumption of the EDs needs to be determined and divided by the total number of successfully received packets at the GW.

$$EE = \frac{E_{ED}}{UL_r}, \tag{3.5}$$

where $E_{ED}$ is the total energy consumption for each ED.

## 3.6 PROPOSED ALGORITHM

We propose the use of fuzzy logic for our ADR algorithm to predict the values of SF and TP on the NS side of the network. The algorithm generates new transmission parameters (SF and TP) according to channel approximations derived from the SNR of the four most recently received data packets (ReceivedPacketList). This reduces computational costs compared to the traditional ADR, which uses 20 data packets to estimate the link quality. For the implementation of the proposed FL-ADR Algorithm, we applied average $\text{SNR}_{margin}$ as the input variable consisting of three membership functions with linguistic variables LOW, IDEAL and HIGH. Triangular membership functions were used in this algorithm. The pattern is determined by the “historyRange” from the ReceivedPacketList. Furthermore, we used two output variables TP-New and SF-New, both consisting of three membership functions with linguistic variables LOW, MEDIUM and HIGH. The $\text{SNR}_{\text{margin}}$ is implemented to modify appropriate SF and TP parameters. The single input multiple output Mamdani fuzzy control system [147] is employed to control the output for optimum adjustment of the SF and TP using Fuzzylite libraries [148]. We designed our membership functions using some of the standards used in [149] using the triangle membership function.

### 3.6.1 The system model

To achieve energy efficiency in the network, LoRaWAN must satisfy the SNR, data rate and power requirements. In our network, we optimise SF and TP at the ED in order to minimise energy utilisation. We consider a LoRa network that uses modulation with a fixed BW of 125 kHz and a fixed payload. The simulation tool mimics the SX1301 digital baseband chip used for GW capabilities and SX1272 for the ED transceiver [150, 151]. The EDs and GWs are static, and randomly distributed and their number does not change in the network. Ten simulations were run with different seeds of random number generators in order to get the statistical confidence of the performance metrics. The network has enabled confirmed traffic. GWs are placed in a hexagonal grid layout where a GW is placed at the centre of each hexagon. We assume that a single GW has the default three receivers working in parallel.

When a data packet is transmitted through a specific LoRa channel and receive paths listening at that channel are unavailable, the data packet is lost. The path loss model between the EDs and the GWs is based on the Log Distance Propagation Model [152]. The effects of signal propagation on signal strength are estimated by a link measurement model at the GW and take into consideration factors like TP and antenna gains both at the transmitter and receiver. The received signal power at the GW is given by (3.6):

$$P_{rx} = \frac{P_{tx} G_a}{L_p}, \tag{3.6}$$

where $P_{tx}$ is the transmit power at the $i^{th}$ ED, $G_a$ is the antenna gain and $L_p$ is the path loss.

We express the power in $dB$ as shown in (3.7):

$$P_{rx}(dB) = P_{tx}(dB) + G_a(dB) - L_p(dB) \tag{3.7}$$

The path loss propagation is given by (3.8):

$$L_p = -10 \log_{10}(d_i^{\alpha} f_c^2 * 10^{-2.8}), \tag{3.8}$$

where $d_i$ is the distance between the $i^{th}$ ED and the gateway, $\alpha$ is the pathloss exponent (3.76), and $f_c$ is the carrier frequency (868.1 MHz).

We assume a simple energy consumption model comprising of four states, namely, transmit, idle, receive and sleep. The energy model links each of the aforementioned states with a different voltage and current utilisation as shown in Table 3.2. We monitor the energy usage of each node throughout the simulation period in order to determine the energy consumption of the network. The model calculates the device energy consumption and estimates the ED's battery life. The total energy consumption for each ED is given by (3.9):

$$E_{ED} = E_{tx} + E_{rx} + E_i + E_s, \tag{3.9}$$

where $E_{tx}$ is the energy consumed when the ED is transmitting a packet, $E_{rx}$ is the energy consumed when the ED is receiving an incoming packet, $E_i$ is the energy consumed when listening for incoming packets and $E_s$ is the energy consumed when the ED is sleep mode.

In our model, we optimise the SF and TP by minimising the SNR requirements of the link. The LoRaWAN specification stipulates the required SNR thresholds that enable signals to be demodulated at the GW according to the current data rate the ED is implementing. LoRa can demodulate signals that are -7.5 dB to -20 dB below the noise floor [6]. We set the range of $SNR_{\text{margin}}$ from -25dB to 25dB [108]. Fuzzy logic is introduced on the NS side to determine how SF and TP can be optimally allocated. The

FL-ADR algorithm determines the average SNR over the four most recent transmissions, determines the minimum required SNR using the current parameters and then calculates the margin. The use of the four most recent packets to estimate the average SNR was adapted from previous research [101, 153]. Using this margin, we implement the fuzzy logic to optimise SF and TP. Furthermore, we set the fuzzy rules and used the Mamdani FLS to complete the operation. $\text{SNR}_{\text{margin}}$ is calculated as given in Equation (2.2).

When the $\text{SNR}_{\text{margin}}$ is high, the data rate can be increased, which implies reducing the SF and TP values. When the $\text{SNR}_{\text{margin}}$ value is low, it implies that the current data rate the ED is using is high and must be reduced by increasing the SF and TP. On the NS side, our proposed FL-ADR algorithm allocates the lowest possible SF above the GW sensitivity and the corresponding TP to the ED. The solution for the optimal transmission parameters for the EDs is obtained using the following procedure:

- the linguistic variable and terms are defined;
- the membership functions are constructed;
- the fuzzy values are created from the crisp input data;
- the rule base evaluates the rules;
- each rule's outcomes are aggregated, and the non-fuzzy values are generated from the output data.

### 3.6.2 The input variable - SNRmargin

The linguistic variable $\text{SNR}_{\text{margin}}$ is decomposed into a set of linguistic terms $\text{SNR}_{\text{margin}} = \{\text{LOW}, \text{IDEAL}, \text{HIGH}\}$.

The crisp input values are mapped to fuzzy linguistic terms by the membership functions and are defined by (3.10) – (3.12) below. Figure 3.2 shows the membership function of the input variable $\text{SNR}_{\text{margin}}$.

The following are the three triangular membership functions used to represent the range of input variable $\text{SNR}_{\text{margin}}$:

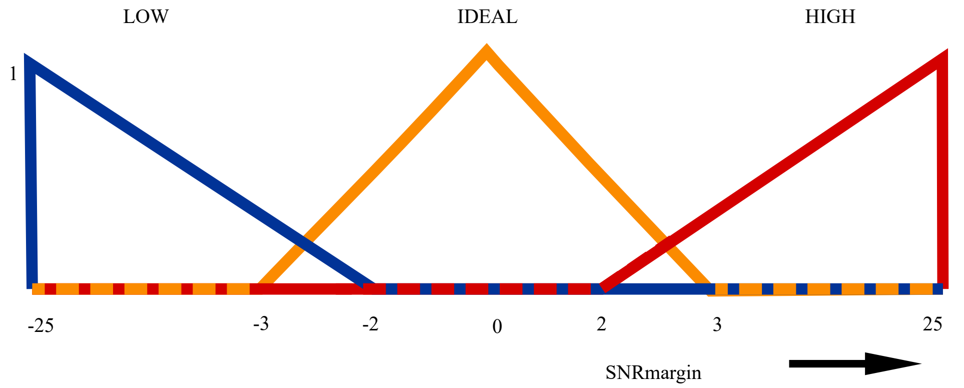


**Figure 3.2.** SNRmargin membership function.

$$\mu_{\text{LOW}}(x) = \begin{cases} 1\,, & \text{if} \quad x \le -25 \\ \frac{-2-x}{23}\,, & \text{if} \quad -25 < x \le -2 \\ 0\,, & \text{otherwise} \end{cases} \tag{3.10}$$

$$\mu_{\text{IDEAL}}(x) = \begin{cases} \frac{x+3}{3}\,, & \text{if} \quad -3 \le x \le 0 \\ \frac{3-x}{3}\,, & \text{if} \quad 0 \le x \le 3 \end{cases} \tag{3.11}$$

$$\mu_{\text{HIGH}}(x) = \begin{cases} 1\,, & \text{if} \quad x \ge 25 \\ \frac{x-2}{23}\,, & \text{if} \quad 2 \le x < 25 \\ 0\,, & \text{otherwise} \end{cases} \tag{3.12}$$

### 3.6.3 The fuzzy rules

In order to regulate the output variable, an FLS constructs a rule base. The fuzzy rules are simple IF-THEN rules with a condition and a conclusion. The rules are set using the knowledge of the LoRaWAN specifications in terms of SNR range, spreading factors and transmission power. The following are the three rules defined in our Fuzzy-Logic based ADR algorithm:

1. “if SNR$_{\text{margin}}$ is HIGH then TPnew is MEDIUM and SFnew is MEDIUM;”
2. “if SNR$_{\text{margin}}$ is IDEAL then TPnew is LOW and SFnew is LOW;”
3. “if SNR$_{\text{margin}}$ is LOW then TPnew is MEDIUM and SFnew is MEDIUM.”

### 3.6.4 The output variable - TPnew

The linguistic variable for transmission power is decomposed into a set of linguistic terms: TPnew $=$ $\{\text{LOW}, \text{MEDIUM}, \text{HIGH}\}$. The membership functions are defined by (3.10) – (3.15) below. Figure 3.3 shows the membership functions for transmission power.

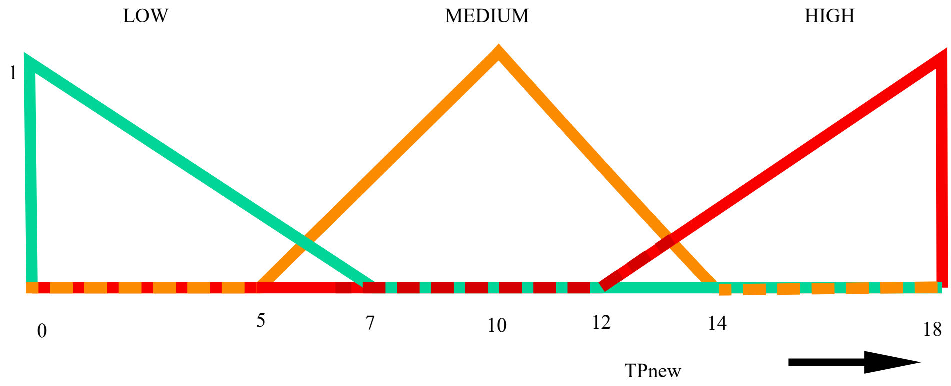


**Figure 3.3.** TPnew membership function.

The following are the three Triangle membership functions used to represent the range of output variable TPnew:

$$\mu_{\text{LOW}}(x) = \begin{cases} 1\,, & \text{if} \quad x \leq 0 \\ \frac{7-x}{7}\,, & \text{if} \quad 0 < x \leq 7 \\ 0\,, & \text{otherwise} \end{cases} \tag{3.13}$$

$$\mu_{\text{MEDIUM}}(x) = \begin{cases} \frac{x-5}{5}\,, & \text{if} \quad 5 \leq x \leq 10 \\ \frac{15-x}{5}\,, & \text{if} \quad 10 < x \leq 15 \end{cases} \tag{3.14}$$

$$\mu_{\text{HIGH}}(x) = \begin{cases} 1\,, & \text{if} \quad x \geq 18 \\ \frac{x-12}{6}\,, & \text{if} \quad 12 \leq x < 18 \\ 0\,, & \text{otherwise} \end{cases} \tag{3.15}$$

### 3.6.5 The output variable - SFnew

The linguistic variable for spreading factor is decomposed into a set of linguistic terms: SFnew = $\{\text{LOW}\,,\text{MEDIUM}\,,\text{HIGH}\}$. The membership functions for spreading factor estimation are defined by (3.16) - (3.18) below and shown in Figure 3.4.

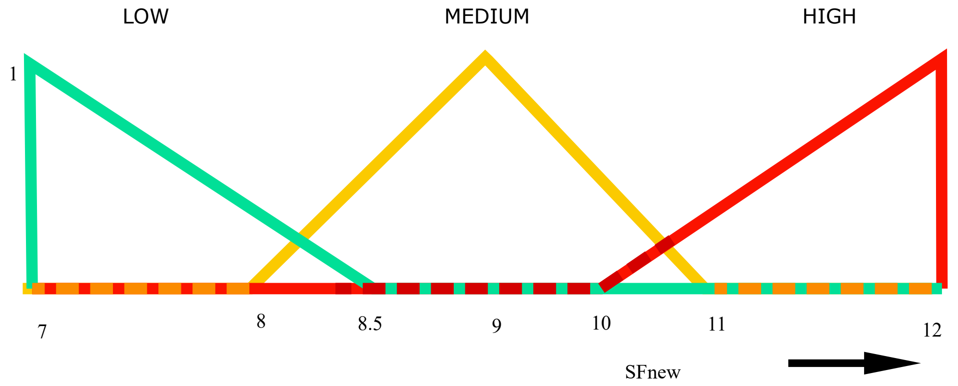


**Figure 3.4.** SFnew membership function.

The following are the three Triangle membership functions used to represent the range of output variable SF-New:

$$\mu_{\text{LOW}}(x) = \begin{cases} 1\,, & \text{if} \quad x \leq 7 \\ \frac{9-x}{2}\,, & \text{if} \quad 7 < x < 9 \\ 0\,, & \text{otherwise} \end{cases} \tag{3.16}$$

$$\mu_{\text{MEDIUM}}(x) = \begin{cases} \frac{x-8}{1.5}\,, & \text{if} \quad 8 \leq x \leq 9.5 \\ \frac{11-x}{1.5}\,, & \text{if} \quad 9.5 < x \leq 11 \end{cases} \tag{3.17}$$

$$\mu_{\text{HIGH}}(x) = \begin{cases} 1\,, & \text{if} \quad x \geq 12 \\ \frac{x-10}{2}\,, & \text{if} \quad 10 \leq x < 12 \\ 0\,, & \text{otherwise} \end{cases} \tag{3.18}$$

Below is the algorithm proposed FL-ADR scheme.

**Algorithm 3.1** The proposed fuzzy-logic based ADR algorithm.

```
Require: $SF = [7,12]$, $TP = [2,14]$, $SNR$
Ensure: $SF$ and $TP$ parameters for each ED
Initialisation: FLEngine $\leftarrow$ Fuzzylite
SNRavg $\leftarrow$ average SNR of last 4 frames
SNRreq $\leftarrow$ demodulation floor (current data rate)
$\mathrm{D_{margin}} \leftarrow$ device margin
$\mathrm{SNR_{margin}} \leftarrow (SNRavg - SNRreq - \mathrm{D_{margin}})$
// $FLEngine$ processes the following:
Define input and output variables $\rightarrow SNR_{margin}, SFnew, TPnew$
Set input and output variable range
Define the membership functions
Set FLS type $\rightarrow$ Mamdani
Add Rule code $\leftarrow$ FLS fuzzy rules
    $->$ "if $SNR_{margin}$ is HIGH then $TPnew$ is MEDIUM and $SFnew$ is MEDIUM"
    $->$ "if $SNR_{margin}$ is IDEAL then $TPnew$ is LOW and $SFnew$ is LOW"
    $->$ "if $SNR_{margin}$ is LOW then $TPnew$ is MEDIUM and $SFnew$ is MEDIUM"
Aggregation $\rightarrow$ Maximum
Defuzzification $\rightarrow$ Centroid
$TPnew, SFnew \leftarrow FLS[SF, TP]$
Transmit $SFnew$ and $TPnew$ to ED
```

### 3.6.6 Configuration details and simulation parameters

A number of open-source LoRaWAN simulation tools have been implemented in ns-3 [154]. The authors in [30] conducted a comprehensive review of the four ns-3 LoRaWAN implementations available, namely ns-3 LoRaWAN [90], lora-ns-3 [142], AWGN LoRaWAN [143] and CSMA LoRaWAN [144]. We resolved to simulate the LoRaWAN network using the ns-3 LoRaWAN module developed by Magrin [90] available at [147]. This model has excellent documentation and has available developers' support. It is a widely used ns-3 LoRaWAN simulator.

For our simulations, we used up to seven GW nodes, one NS node and between 100 and 300 ED nodes in a 10 km × 10 km network, sending data packets at different time intervals. Tables 3.2 and 3.3 show the parameters used in the LoRaWAN simulation. We coded our algorithms inside the ADR component code of the ns-3 LoRaWAN module. We analysed the system performance of different ADR models, namely, the standard ADR model, which we term Semtech-ADR, the ADR model implemented in the ns-3 LoRaWAN module, which we term ns-3-ADR and our proposed fuzzy logic-based ADR known as FL-ADR. We performed two different evaluations and analyses. In the first evaluation, we used 100 EDs and changed the Application Data Packet Rate to transmit 1 packet per 300 s, 600 s, 900 s, 1200 s and 1500 s. In the second evaluation, we kept the application data rate constant at 1 packet per 600 s and varied the number of EDs to 100, 150, 200, 250 and 300 and analysed the performance. The simulation was configured to simulate for 3.3 h. Tables 3.2 and 3.3 show some of the important parameters that we used while evaluating the performance of the typical LoRaWAN network. Table 3.2 below shows the energy model parameters used by ED nodes of ns-3 LoRaWAN simulation.

**Table 3.2.** Energy model parameters.

| Parameter | Value |
|---|---|
| Initial Energy of EDs | 10000 J |
| Supply Voltage | 3.3 V |
| Stand by Current | 0.0014 A |
| Tx Current | 0.028 A |
| Sleep Current | 0.0000015 A |
| Rx Current | 0.0112 A |

**Table 3.3.** Network parameters.

| Parameter | Value |
|---|---|
| Number of EDs | 100, 150, 200, 250, 300. |
| Topographical Area of EDs | 10,000 m × 10,000 m |
| Number of GWs | 7 |
| Number of NS | 1 |
| Number of EDs | 100, 150, 200, 250, 300. |
| MType | CONFIRMED_DATA_UP |
| Data Rate control | Enabled |
| ADR | Enabled |
| End Device Mobility | Disabled |
| Channel Loss Model | LogDistancePropagationLossModel |
| Channel Propagation Delay Model | ConstantSpeedPropagationDelayModel |
| Simulation Time | 3.3 h |
| App. Data Packet Rate | 1 packet per 300 s, 600 s, 900 s, 1200 s, 1500 s. |

## 3.7 RESULTS AND DISCUSSION

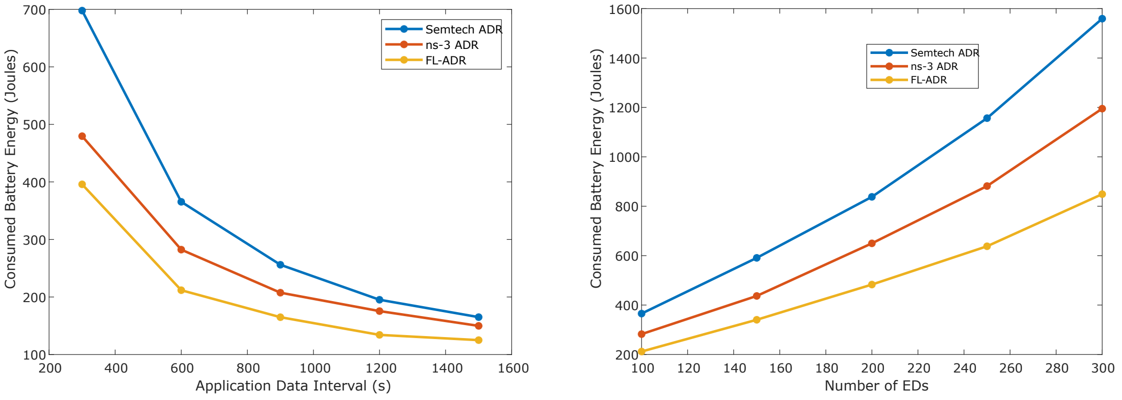
This section includes a performance analysis of our proposed scheme as well as the numerical output of our simulations. Using two additional schemes as benchmarks, we evaluated the performance of our proposed algorithm. In this thesis, we mention that computational complexity is a critical factor that can significantly impact the performance of the ADR algorithm. Computational complexity refers to the number of resources required to run the algorithm, particularly time and memory requirements expressed as a function n → f(n), where n is the size of the input and f(n) is the worst-case complexity or the average-case complexity. The computational complexity of FL-ADR can be classified as linear, having a constant complexity of $\mathcal{O}(1)$. The dominant factors contributing to the complexity are the fuzzy inference system operations, specifically the number of membership functions and fuzzy rules defined. Other factors such as averaging SNR values, calculating demodulation floor, and transmitting data have less significant impact on the overall complexity. Overall, the fuzzy logic portion of the algorithm determines the dominant computational complexity. Table 3.4 shows some characteristics of the three ADR schemes being compared. In this analysis, we used six metrics (Total Energy Consumption (ET), Confirmed Packet Success Rate (CPSR), Uplink Packet Delivery Ratio (UL-PDR), Interference/Collision Rate ($I_{PR}$), Lost-Because-Busy Rate ($L_{PR}$)) and Energy Efficiency in the evaluation of the LoRaWAN network performance. The charts below show the comparison in performance between Semtech-ADR, ns-3-ADR and our proposed FL-ADR scheme, indicating network performance using these metrics. We use the six metrics we are considering for performance analysis.

**Table 3.4.** Features of the three ADR algorithms under consideration.

| **Semtech-ADR** | **ns-3-ADR** | **FL-DR** |
|---|---|---|
| 20 packets | 4 packets | 4 packets |
| Maximum SNR | Minimum SNR | Average SNR |
| $\text{SNR}_{\text{margin}}$ (Equation (2.2)) | $\text{SNR}_{\text{margin}}$ calculation excludes $\text{D}_{\text{margin}}$ | $\text{SNR}_{\text{margin}}$ (Equation (2.2)) |
| $\text{SNR}_{\text{margin}}/3$ | $\text{SNR}_{\text{margin}}/3$ | No steps required |
| Uses 3 dB steps to adjust TP | Uses 2 dB steps to adjust TP | Uses fuzzy logic |

### 3.7.1 Performance in terms of total energy consumption

Figures 3.5(a) and 3.5(b) show the performance of the three different LoRaWAN ADR implementations in terms of total energy consumption. The total energy consumption (ET) comprises the energy utilised by all the EDs. Figure 3.5(a) considers application data intervals. The FL-ADR showed superior performance with respect to the total energy consumed. This is attributed to the ideal SNR margin obtained from the FIS, ensuring the effective assignment of SF values at minimal transmission power. As the data packet interval increases, less energy is expended because the probability of packet collision and retransmission is reduced. According to the simulation results, the global network performance shows that every time the interval is increased by 300 s, the overall network energy consumption reduces at every step by approximately 46%, 22%, 18% and 6%, respectively, across the three algorithms. This aligns with the fact that a low duty cycle is ideal for LoRaWAN as per specifications. Figure 3.5(b) provides a comparison of energy consumption against different numbers of node density at a constant application data interval of 600 s. As more nodes are added onto the network, it is expected that the total energy consumption will increase. The simulation results show that the proposed FL-ADR algorithm conserves over 43% of the battery energy compared to Semtech-ADR and 14% saving compared to ns-3-ADR, respectively.

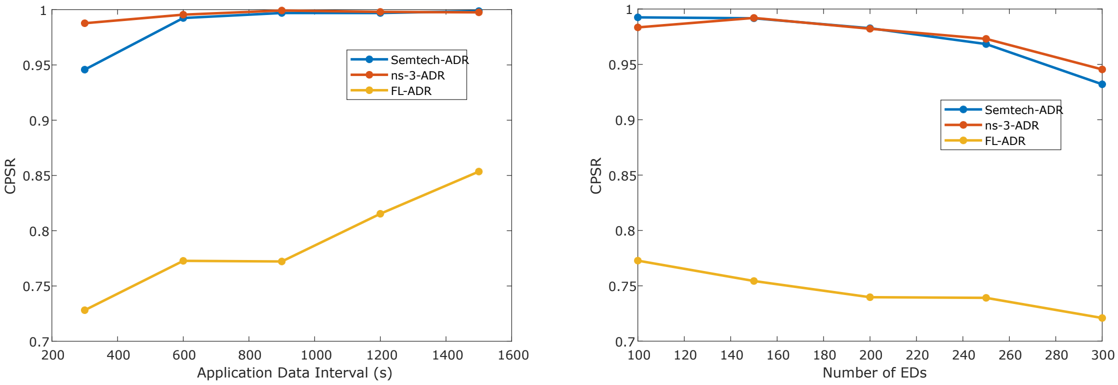


**(a)** **(b)**

**Figure 3.5.** The total energy consumption: (a) data interval vs. total consumed energy; (b) no. EDs vs. total consumed energy.

### 3.7.2 Performance in terms of confirmed packet success rate

Figures 3.6(a) and 3.6(b) show the performance of the three ADR implementations of LoRaWAN in terms of confirmed packet success rate. This is the probability that the transmitted uplink packets and their corresponding downlink packets are appropriately received by the network server and the ED, respectively, in at least one of the transmission attempts available. Our proposed algorithm FL-ADR is outperformed by the other Semtech-ADR and ns-3-ADR algorithms. The effect of the gateway density makes the CPSR close to one for the better-performing algorithms while FL-ADR ranges between 0.7 and 0.8 [155]. The results show that CPSR tends to increase as the application data interval increases. This is because longer intervals between transmissions reduce congestion and therefore reduce the probability of interference or packet collision. As the node density increases, the CPSR decreases as a result of an increase in the probability of interference or collision. An increase in network size results in more attempts to transmit packets and a drop in the ratio of successfully received packets. For example, when the node density is 150, the value of FL-ADR CPSR is 0.754, while that of ns-3-ADR is 0.991. The CPSR decreases when the node density increases to 300 nodes to 0.721 for FL-ADR and 0.945 for ns-3-ADR, respectively.

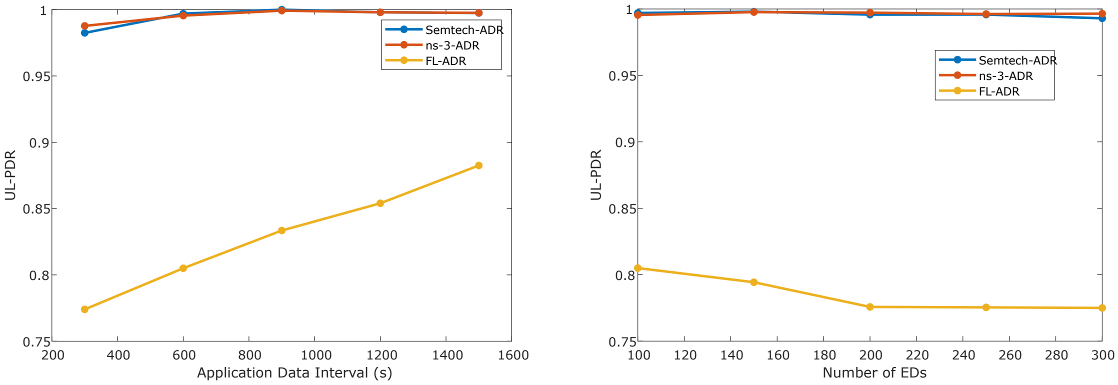


(a) (b)

**Figure 3.6.** Successful reception rate: (a) data interval vs. avg. reception rate/load; (b) no. EDs vs. reception rate/load.

### 3.7.3 Performance in terms of uplink packet delivery ratio

The probability that an uplink packet ($UL_s$) is correctly received (whether or not the ACK is requested) is defined as Uplink Packet Delivery Ratio (UL-PDR). We measure the ratio of uplink packets successfully delivered to the GW over those generated at the EDs. In Figure 3.7, the FL-ADR shows poorer performance in terms of UL-PDR compared to the other two algorithms. More differences in performance are apparent in the two unique metrics considered below even though there is a difference when comparing the UL-PDR and CPSR performance, especially between Semtech-ADR and ns-3-ADR. This could be a result of a potentially high SF that leads to a reduced data rate. While the algorithm consumes less energy and avoids interference, the signal becomes weak, potentially falling below the receiver's sensitivity threshold.

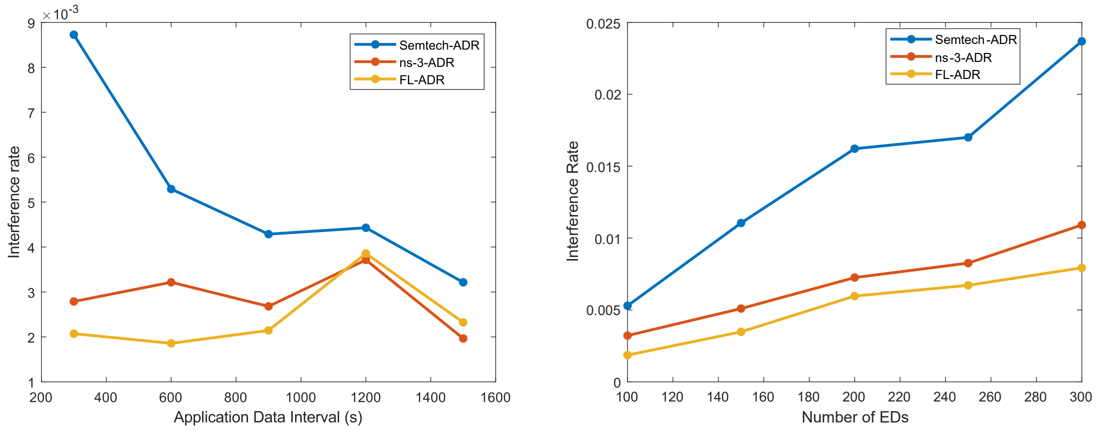


**(a)** **(b)**

**Figure 3.7.** Uplink packet delivery ratio: (a) data interval vs. uplink packet delivery ratio; (b) no. EDs vs uplink packet delivery ratio.

### 3.7.4 Performance in terms of interference/collision rate

Figures 3.8(a) and 3.8(b) show the performance of the three different ADR schemes considering the interference/collision rate. It is the rate of packet loss when the packet is correctly locked on by the GW, but due to interference from overlapping packets, the GW fails to receive the packet. The performance of FL-ADR performs slightly better than the ns-3-ADR, while the Semtech-ADR is marginally underperforming. The slight increase in interference rate at a 1200 s interval is peculiar. This is the result of a bug in the simulation module and is currently under investigation. Interference is minimal in this network attributed to the effect of multiple gateways. As the node density increases, the network becomes more prone to interference/collisions. Typically, as the application data interval increases, the probability of interference/collision decreases.

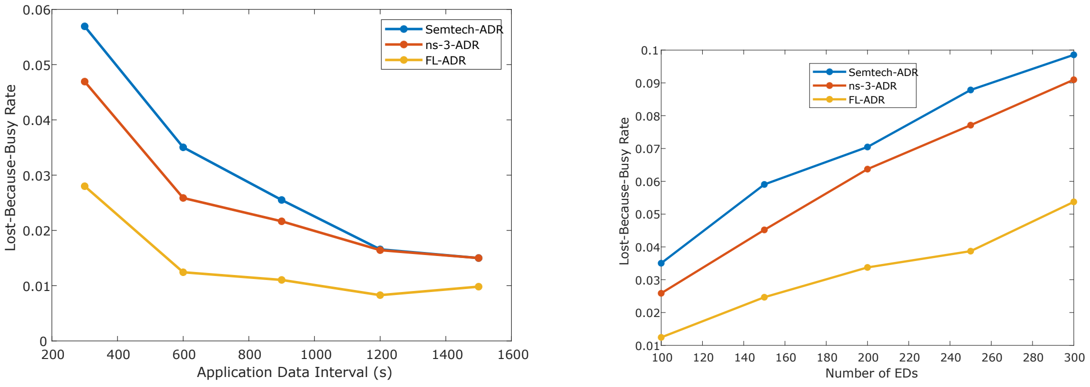


**(a)** **(b)**

**Figure 3.8.** Interference/collision rate: (a) data interval vs. interference/collision rate; (b) no. EDs vs. interference/collision rate.

### 3.7.5 Performance in terms of lost-because-busy rate

Figures 3.9(a) and 3.9(b) show the three different ADR performances in terms of Lost-Because-Busy rate. This occurs when packets are lost due to GW transmission, the disruption of packet reception due to the broadcast of a downlink packet from the GW. Typically, the ratio decreases as the application data interval increases because there is less traffic to the GWs to receive UL and transmit DL messages. Where ED density is increasing, this ratio tends to increase because the GWs are flooded with transmissions. This metric provides more detail in the behaviour of the algorithms where FL-ADR performs marginally better than its two counterparts as shown in Figure 3.9. The LoRa standard recommends the first DL receive window (RX1) to be unlocked on a similar channel used in the uplink, while the second window (RX2) is unlocked in the reserved downlink channel. While the GW is transmitting a DL message, no UL messages are transmitted. Therefore, as the node density increases, the number of UL and DL packets increases causing delays.



**(a)** **(b)**

**Figure 3.9.** Lost-Because-Busy Rate: (a) data interval vs. avg. lost-because-busy rate; (b) no. EDs vs. lost-because-busy rate.

### 3.7.6 Energy efficiency in terms of correctly received packets

The ratio of the total number of packets received at the gateway to the total amount of energy used by the network to send those packets is known as energy efficiency. Figure 3.10 below shows the energy consumed per packet calculated for the three algorithms under consideration. For these results, the application data interval was 600 s, implying that 20 packets were sent per ED during the simulation period. Packets sent range from 2000 to 6000 depending on the number of EDs. The FL-ADR is more energy efficient compared to the Semtech-ADR and the ns-3-ADR, showing that the proposed ADR is efficiently adjusting SF and TP despite a trade-off with CPSR and $UL_{PDR}$.

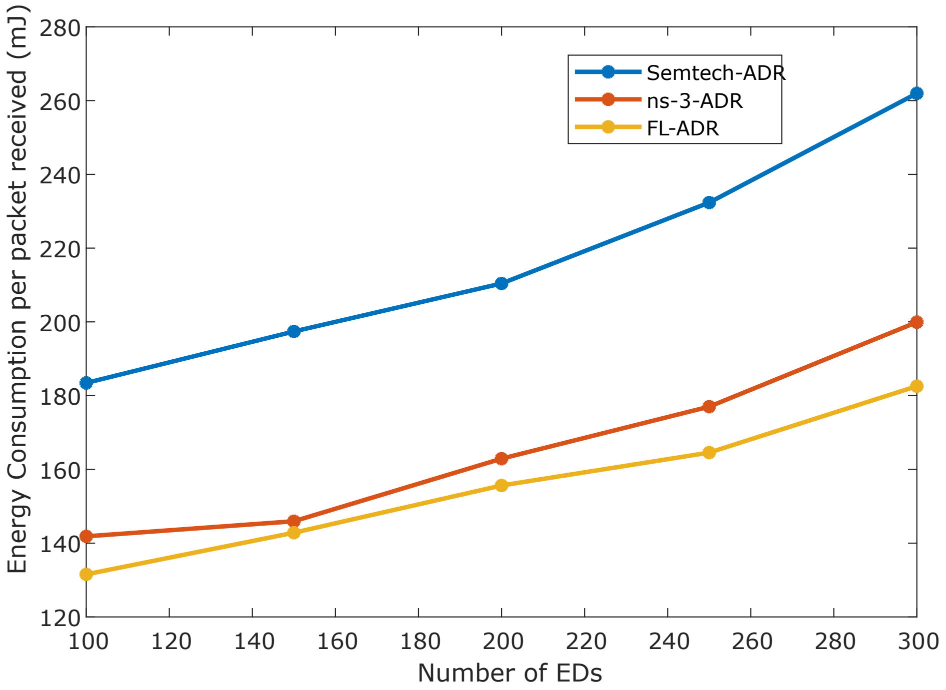


**Figure 3.10.** Energy Efficiency in terms of correctly received packets.

From the results presented in the above sections, we observe that the two unique metrics $I_{PR}$ and $L_{PR}$ were able to showcase the intricate differences in performance better than CPSR and UL-PDR, which did not provide that much differentiation between the models, particularly under ideal network conditions. Where multiple gateways are implemented, CPSR and UL-PDR may have a value almost equal to one (100%) such that it is difficult to distinguish the performance of the models only by using CPSR and UL-PDR. In terms of energy consumption, FL-ADR provided the best performance, saving up to 14% of energy per ED node in this 3.3 h simulation scenario compared to the ns-3-ADR and 43% compared to Semtech-ADR. Although the FL-ADR is more energy efficient, this is achieved with a drop in performance in terms of CPSR and UL-PDR. This may be due to a potentially high signal-to-noise ratio (SNR) that results in a decreased data transmission rate. Although the method has the advantage of lower energy consumption and avoidance of interference, it may result in a weakened signal that could potentially fall below the sensitivity threshold of the receiver. This results in packet loss despite the low energy consumption and interference. This phenomenon will be the focus of future investigations. This algorithm could be used in applications where energy consumption is of utmost priority in the QoS requirements.

## 3.8 CHAPTER SUMMARY

In this chapter, a novel fuzzy-logic-based adaptive data rate scheme for energy-efficient LoRaWAN communication, referred to as FL-ADR, was introduced. The performance of the proposed scheme was evaluated through extensive simulations. The methodology employed in this scheme was discussed in Section 3.5, where the system performance parameters are presented. Section 3.6 provided a comprehensive discussion on the system model, proposed algorithm, and the variables utilised in the fuzzy logic system. Furthermore, the configuration details and simulation parameters of the network were presented to ensure clarity and reproducibility. The results presented in Section 3.7 demonstrated that the FL-ADR scheme, based on fuzzy logic, exhibited notable advantages in terms of reduced energy consumption when compared to existing Semtech-ADR and ns-3-ADR schemes. Despite achieving better overall performance, it is important to note that the FL-ADR scheme led to a decrease in the confirmed packet success ratio and uplink packet delivery ratio for this multi-gateway network. To gain a deeper understanding of the CPSR and UL-PDR performance, two distinct metrics, namely $I_{PR}$ and $L_{PR}$, were employed for analysis. These metrics provided additional insights into the network's physical layer performance. Our proposed scheme is a novel energy-efficient ADR algorithm that reduces energy wastage in EDs in a LoRaWAN network by improving interference/collision rates. A system model that can improve energy efficiency without compromising the CPSR and the UL-PDR is proposed in Chapter 4.

# CHAPTER 4 COLLISION AVOIDANCE ADR ALGORITHM

## 4.1 CHAPTER OVERVIEW

LoRaWAN networks experience significant interference, which have an impact on the packet delivery ratio, energy utilisation and overall network performance. To address the challenge, we introduce a novel ADR framework, SNR-based Spreading Factor Interference Rate controlled Adaptive Data Rate Algorithm (SSFIR-ADR), that leverages randomised spreading factor allocation to minimise energy consumption and reduces packet collisions while maintaining optimal network performance. A system model that can improve energy efficiency without compromising the confirmed packet success rate (CPSR) and the uplink packet delivery ratio (UL-PDR) is developed. The network implements a single gateway linking multiple end nodes to a network server. The simulations show that our proposed method works better than the old LoRaWAN ADR scheme in terms of how much energy it uses, how many packets it delivers, and how much interference it causes for different application data intervals. Section 4.2 provides a technical background of the problem. Section 4.3 presents the related literature and the contributions of this chapter. Section 4.4 presents the system modelling of the new ADR algorithm. In Section 4.5 the operation of the proposed ADR algorithm is presented. Section 4.6 presents the simulation results and discussions and finally, Section 4.7 provides the conclusion of the chapter.

## 4.2 LONG RANGE WIDE AREA NETWORKS

The Internet of Things (IoT) is a paradigm shift that has revolutionised wireless network technologies worldwide, enabling many end devices (EDs) to be supported while maintaining low communication rates and high energy efficiency. IoT aspects improve our quality of life, automate various operations, and minimise energy usage, which reduces greenhouse gas emissions. One such IoT technology, Low Power Wide Area Network (LPWAN), has gained widespread adoption due to its low cost, battery-operated end devices, wide area coverage, and low bit rates. One of the many LPWAN technologies available, Long Range Wide Area Network (LoRaWAN) has rapidly grown in popularity due to its straightforward, versatile deployment and use of the sub-GHz unlicensed industrial, scientific, and medical (ISM) frequency bands. LoRaWAN contributes to various IoT applications which enhance the quality of life, including smart homes [156], smart healthcare [157], smart agriculture [158] and smart cities [159]. A comparison of LoRaWAN and other competing LPWAN technologies including Sigfox and NBIoT is presented in [10, 12].

The LoRa physical layer utilises the chirp spread spectrum (CSS) modulation technique to modulate the transmitted signal. CSS enables the adjustment of the data transmission rate derived from a range of transmission parameter settings, which include bandwidth (BW), coding rate (CR), transmission power (TP) and spreading factor (SF) [43]. These settings are essential for evaluating the interference and noise robustness of the devices, transmission range, data rate, and energy utilisation. As a result, LoRaWAN is an important LPWAN technology that can meet the Quality of Service (QoS) requirements of diverse IoT applications [160].

In this work, we focus on the interference challenge faced by LoRaWAN networks, which can cause packet collisions because of an increase in concurrent transmissions or channel conditions. Interference can significantly impact the network's performance by causing increased packet error rates, increased latency, and decreased signal quality, ultimately leading to lower reliability and reduced communication range. Studies have been undertaken which focus on the capabilities and constraints of LoRaWAN [81, 161]. As more devices continue being added to the IoT network, the probability of interference and collision of data packets increases [143, 162]. The number of inter-connected IoT end devices is anticipated to surpass 55 billion by 2025 [163]. Most of these devices are deployed in specified and sometimes hard-to-reach locations, necessitating that they operate for extended periods on battery power. Hence, decreasing power utilisation is crucial for the Internet of Things. To mitigate these effects, LoRaWAN networks typically use frequency hopping and adaptive data rate schemes, which dynamically adjust the transmission settings to minimise the impact of interference [164].

Adaptive Data Rate (ADR) is a protocol specified by LoRaWAN that enables the allocation of spreading factors [6, 27]. The ADR protocol controls transmission parameters such as data rate, transmission range, reliability, and energy expenditure by dynamically adjusting the spreading factor in relation to the link budget for each end device within the LoRaWAN network. The CSS modulation technology has pseudo-orthogonal properties with different spreading factor signals that can support multiple end devices in one channel. However, this quasi-orthogonality also results in interference and noise between spreading factors that can significantly affect the link performance [103, 165–167]. While ADR improves the transmission efficiency of end devices in LoRaWAN, increasing the network size leads to packet collisions, which in turn increase interference, decrease range, and reduce data rates [80, 168–170]. This leads to increased interference, decreased range, and decreased data rates.

Energy efficiency is a chief consideration in the design of ADR schemes for LoRaWAN networks, as the battery life of end nodes can be a limiting factor in network operation. It is thus desirable to find additional mechanisms that deal with this phenomenon. In this study, we propose SSFIR-ADR, an adaptive data rate algorithm that optimally allocates spreading factors, reducing packet collision to improve the packet delivery ratio in the LoRaWAN network without compromising energy efficiency. Our proposed ADR scheme is designed to improve packet delivery while taking into account energy efficiency for LoRa using confirmed traffic. To the best of our knowledge, such a framework has not been developed in the literature. The key contributions of this work are defined as follows:

- The analysis of the impact of improving the standard LoRaWAN ADR by minimising interference and avoiding collisions.
- The design of an ADR model with collision avoidance and minimised interference.
- The proposal of a stochastic probability model to restrict packet retransmission that demonstrates an improvement in packet delivery ratio and energy saving.

### 4.2.1 TECHNOLOGICAL BACKGROUND

The LoRaWAN network infrastructure consists of three major elements, namely end devices, gateways (GW) and a network server connected in a star-of-star topology. EDs are battery-powered endpoints such as sensors or actuators that transmit to and receive data from the network using the LoRa PHY layer technology. LoRaWAN is classified as the media access control (MAC) layer. The EDs transmit data packets via the GW for onward transmission to the network server (uplink packets) and the NS transmits data through the GW to the EDs (downlink packets). There is no peer-to-peer communication between the EDs. The GW is an intermediary between the EDs and the NS connected through an IP-based backhaul connection. The Network Server is responsible for the network management and controlling access to it. The NS handles the authentication of EDs, manages the scheduling of transmissions, and coordinates the distribution of network transmission parameters. The NS then connects to numerous application servers to be accessed by users. LoRaWAN provides the Internet of Things with three distinct Classes A, B, and C to accommodate various application protocols. Downlink latency varies according to the device class and therefore there is a tradeoff between latency and energy utilisation in LoRaWAN [6]. There are two reasons why a sent packet is not correctly received in LoRaWAN: i) in cases where the signal falls below the required SNR threshold and ii) in situations where a collision occurs and the signal strength is insufficient compared to the noise. Table 4.1 presents the sensitivity and signal-to-noise ratio (SNR) thresholds linked with various spreading factors within the 868 MHz band.

**Table 4.1.** SNR and sensitivity thresholds per spreading factor.

| Spreading Factor | Required SNR [dB] | Sensitivity [dBm] |
|---|---|---|
| 7 | -7.5 | -123 |
| 8 | -10 | -126 |
| 9 | -12.5 | -129 |
| 10 | -15 | -132 |
| 11 | -17.5 | -134.5 |
| 12 | -20 | -137 |

### 4.2.2 LoRa physical layer

Four key LoRa transmission parameters include transmission power, bandwidth, coding rate, and spreading factor. BW is the frequency range, error correction is provided by CR, and SF represents the data spreading across time. The transmission factors influence radio range, time-on-air, noise robustness, data rate (DR), and receiver decoding [100]. LoRa modulation utilises spreading factors between 7 and 12 to find a balance between coverage range and DR. LoRa symbols are made up of 2SF chirps, distributed across the whole frequency domain. Depending on the regional parameters, LoRaWAN operates at 125kHz, 250kHz or 500kHz bandwidth [126] [26]. LoRa uses a frequency shift CSS technology that outputs $\mathrm{M} = 2^{\mathrm{SF}}$ possible signal waveforms within a given bandwidth BW where the symbol duration is given by $\mathrm{T_s} = \frac{\mathrm{M}}{\mathrm{BW}}$ [171]. The LoRa modem employs a coding rate, providing improved interference and decoding error protection. The LoRa specification prescribes CR values of 4/5, 4/6, 4/7 or 4/8. A high CR value indicates more error-correcting bits and therefore more robust protection for the data transmitted. The disadvantage is an increase in the ToA which drains the battery power. Transmission power is a parameter that could also be adjusted to enhance communication performance.

### 4.2.3 Interference susceptibility of LoRaWAN

Asymmetric interference occurs between wireless sensor networks, including LoRaWAN networks and other wireless protocols. LoRaWAN networks, in particular, may encounter different kinds of interference that could drastically affect network performance. Wideband interference can be caused by other wireless devices operating on similar frequencies such as microwave ovens, cordless phones, electrical noise from power lines, and even natural sources such as lightning strikes. Narrowband interference is generally the result of the presence of signals that occupy a small frequency band, typically a few kilohertz or less, within the frequency band like Bluetooth.

Within the LoRaWAN network itself, there exists a form of interference known as co-spreading factor (co-SF) and inter-spreading factor (inter-SF) interference [166, 170]. Co-SF interference occurs when two LoRaWAN devices use the same spreading factor and transmission occurs concurrently and on the same frequency. This can result in collisions and lost packets, leading to reduced network performance unless one of the signals is 6dB stronger than the other, called the capture effect expressed in (4.1). Given two colliding EDs, $\mathrm{ED_i}$ and $\mathrm{ED_j}$ using the same SF s, with average received power $P_{rx_i}$ and $P_{rx_j}$ respectively:

$$C_{ij}^{s} = \begin{cases} 1\,, & \text{if} \quad P_{rx_i} - P_{rx_j} \leq 6, \\ 0\,, & \text{otherwise}\,. \end{cases} \tag{4.1}$$

Inter-SF interference, on the other hand, occurs when two LoRaWAN devices using different SFs transmit simultaneously on the same frequency. This can result in the degradation of the signal-to-noise ratio (SNR) and a rise in the bit error rate (BER) of the received signal resulting in increased energy consumption. Demodulation of the transmitted packets occurs if the received power differential exceeds their signal-to-interference-plus-noise ratio (SINR). Due to the rapid growth in the IoTs, especially in urban areas, interference becomes a major concern that requires immediate solutions as the sensors are battery operated and their lifetime is limited and therefore needs to be extended. The quasi-orthogonality of spreading factors means that they have minimal interference with each other. This is because LoRaWAN operates in unlicensed frequency bands, where multiple devices can transmit data simultaneously, and interference can occur between devices using the same or different spreading factors. Table 4.2 shows the interference thresholds per spreading factor. Req is the required SF and Int is the interfering SF. These SIR thresholds are empirical values.

**Table 4.2.** Interference thresholds per spreading factor [172].

| Req\ Int | SF7 | SF8 | SF9 | SF10 | SF11 | SF12 |
|---|---|---|---|---|---|---|
| SF7 | 6 | -16 | -18 | -19 | -19 | -20 |
| SF8 | -24 | 6 | -20 | -22 | -22 | -22 |
| SF9 | -27 | -27 | 6 | -23 | -25 | -25 |
| SF10 | -30 | -30 | -30 | 6 | -26 | -28 |
| SF11 | -33 | -33 | -33 | -20 | 6 | -29 |
| SF12 | -36 | -36 | -36 | -36 | -36 | 6 |

### 4.2.4 LoRa adaptive data rate

The LoRaWAN standard employs an integral feature known as Adaptive Data Rate, which serves multiple essential purposes. ADR is designed to prolong the battery life of EDs, optimise Quality of Service requirements, enhance overall network capacity, and maximise data throughput. The achievement of these objectives relies on the dynamic management of spreading factor and transmission power. The work in [29] presents an overview of the LoRaWAN ADR framework. The ADR system operates at both the ED and NS sides. EDs play a role in determining whether ADR should be activated by setting a specific bit. Once this bit is set, the NS takes charge of regulating the transmission settings and issuing the necessary ADR commands to the ED. Periodically, the ED verifies whether the network server is successfully receiving uplink packets, which is confirmed through SNR link margin feedback sent by the NS. In cases where uplink transmissions fail to reach the gateway, the primary objective of the ED is to improve the status quo by increasing the spreading factor, hence decreasing the data rate. Additionally, if a downlink packet is not received within a programmable number of frames, the ED takes proactive action by increasing the SF for the subsequent uplink packet [6]. This results in an improvement in the transmission range and the possibility of communicating with the GW. By dynamically adjusting these transmission parameters, LoRaWAN's ADR effectively adapts to varying environmental conditions, ensuring optimised performance and efficient resource utilisation in the network.

## 4.3 RELATED LITERATURE

Adaptive data rate schemes have been proposed for LoRaWAN networks to address the issue of interference and packet collisions, which can severely impact the network's performance. In this section, we review some of the related research on ADR schemes for LoRaWAN. Optimal resource allocation in ADR implementation still requires further research as transmission delays, interference and energy efficiency remain a topical issue. Some research has been done addressing interference and packet collision issues in LoRa networks [103, 167, 173] but is not exhaustive. ED mobility is a phenomenon that is gaining ground [123, 153, 174] and poses its own challenges of frequently varying network conditions. One of the earliest ADR schemes propositioned in literature is a fair adaptive rate algorithm developed by [106] wherein the authors propose a solution to adjust ADR due to network congestion using supervised learning. This technique improves the standard ADR by reducing the probability of ineffective SF adjustments. However, due to the learning process and the feedback required for every transmission, there is an increase in the transmission latency.

EXPLoRa is an algorithm proposed in [104] that considers dense networks to decrease the collision rate and improve throughput. The algorithm distributes equally the number of end devices utilising different SFs (EXPLoRa-AT and another that allocates the SFs by equalising the time-on-air (ToA) between different nodes. This method ensures channel usage fairness, although gateway distances are ignored. This approach involves periodically monitoring and managing network behaviour from a centralised entity. The work in [175] introduces CA-ADR, a collision-aware algorithm which determines optimal data rates using the average SNR of recent packets as a benchmark and the orthogonality of distinct SFs to decrease the probability of collision. This algorithm performs better in comparison with state-of-the-art algorithms albeit in a limited network radius where there are no connectivity constraints. Collision Avoidance Resource Allocation (CARA) is proposed in [176] wherein the ADR algorithm increases network capacity while decreasing the number of collisions. CARA partitions the available bandwidth of the wireless channel into resource sections corresponding to each channel and SF. This algorithm increases throughput but increases transmission time and energy consumption.

A link margin parameter was used in the ADR algorithm in [177] to account for inaccurate link quality estimates. The algorithm resulted in improved SF allocation and a decrease in energy utilisation on individual nodes. A game theory-based strategy was used in [178] to manage the assignment of SFs to different EDs using the same spreading factor. They used varying time periods for these EDs to share the spreading factor, preventing interference amongst EDs transmitting concurrently. An ADR algorithm that exploits the quasi-orthogonality of spreading factors to create new channels was developed in [32]. They delivered higher throughput compared to legacy ADR algorithms but only used SF7-SF9 to evaluate their proposed scheme. In our previous work [94] we used fuzzy logic to develop an energy-efficient ADR algorithm, FL-ADR. Although this proposed scheme was more energy efficient compared to legacy schemes, there was a decrease in the packet delivery ratio. In [179], the authors proposed an ADR algorithm that assigns SFs by balancing the time-on-air of packets transmitted by every ED, whereas in [114], an optimum section of SFs is determined to allocate SF and TP to minimise the chance of packet collision within each SF cluster. The algorithms mentioned above focus on the protocol strategy and depend on basic contention models. Zorbas et al. [180] used the average packet success probability of every spreading factor to determine the spreading factor boundaries in a LoRaWAN cell but limited the radius to 500m. In our work, we extend our optimal SF allocation to 5km radius.

Overall, these studies establish the importance of ADR schemes in LoRaWAN networks and highlight the need for adaptive and intelligent approaches to address the challenges of interference and packet collisions. Realisation remains a long way off and remains an open research area despite solutions being proposed. In this work, we develop an ADR algorithm with collision avoidance and interference management that improves energy efficiency without compromising the packet delivery ratio.

## 4.4 METHODOLOGY

### 4.4.1 System model

We consider a LoRaWAN network using European regional parameters with confirmed traffic transmissions for Class A end devices. The network uses modulation with a fixed bandwidth of 125kHz and consists of one GW positioned in the centre of the coverage region. EDs are static and homogenous and located randomly with uniform distribution in the coverage area. The network covers a topographical area of 10km by 10km. EDs generate packets of fixed payload for a given SF at the same application data interval regardless of the proximity from the GW. The transmission start time for each ED is chosen randomly. In our algorithm, the NS uses the average SNR values of the previous four packets sent by the ED to estimate the link quality, in comparison with the standard ADR algorithm that uses the maximum SNR value of twenty packets, saving on computational costs [94]. In this context, the traffic model for each ED is considered to be periodic and uniformly distributed. This means that the data transmission from each ED occurs at regular intervals and is spread evenly across the network. We use the Log Distance Propagation path loss model [152]. This model provides a way to estimate how the signal strength decreases as it travels over a distance, taking into account factors like attenuation and interference. The system model incorporates the interference arising from simultaneous uplink transmissions on a specific desired uplink transmission. A transmitted packet will be received or dropped based on the sensitivity values given in Table 4.1. Therefore, SF should be allocated to an ED ensuring that the received signal strength is greater than the receiver sensitivity as shown in (4.2) below.

$$SNR_{margin} = SNR_{avg} - SNR_{thresh} - D_{margin}, \tag{4.2}$$

where $SNR_{avg}$ is the average SNR of the packets in the ReceivedPacketList, $SNR_{thresh}$ is the minimum SNR threshold and $D_{margin}$ is the device margin. The received signal power at the GW in dB is given in (4.3):

$$P_{rx}(dB) = P_{tx}(dB) + G_a(dB) - L_p(dB), \tag{4.3}$$

where $P_{tx}$ is the transmit power at the $i^{th}$ ED, $G_a$ is the antenna gain, and $L_p$ is the path loss.

The path loss propagation is given by:

$$L_p = -10\log_{10}(d_i^{\alpha} f_c^2 * 10^{-2.8}), \tag{4.4}$$

where $d_i$ is the distance between the $i^{th}$ ED and the gateway, $\alpha$ is the pathloss exponent (3.76) and $f_c$ is the carrier frequency (868.1MHz).

The network is partitioned into K regions wherein K represents the number of available spreading factors. The simulations are conducted using ns-3 simulator [154] using a LoRaWAN module developed by [145]. The simulation is carried out with a fixed number of EDs and it is assumed that their number does not change during the simulation. Figure 4.1 shows a NetAnim output of the LoRaWAN network scenario implementing one hundred EDs. The simulation parameters are presented in Table 4.3. A four-state energy consumption model is assumed, comprising the transmit, idle, receive, and sleep states. Table 4.4 shows how the energy model links voltage and current usage to each state. To compute network energy usage, we track each node's energy usage during simulation. The model estimates ED battery life and energy consumption. Total energy consumption for each ED is given by:

$$E_{ED} = E_{tx} + E_{rx} + E_i + E_s, \tag{4.5}$$

where $E_{tx}$ is the energy consumed when the ED is transmitting a packet, $E_{rx}$ is the energy consumed when the ED is receiving an incoming packet, $E_i$ is the energy consumed when listening for incoming packets and $E_s$ is the energy consumed when the ED is sleep mode.

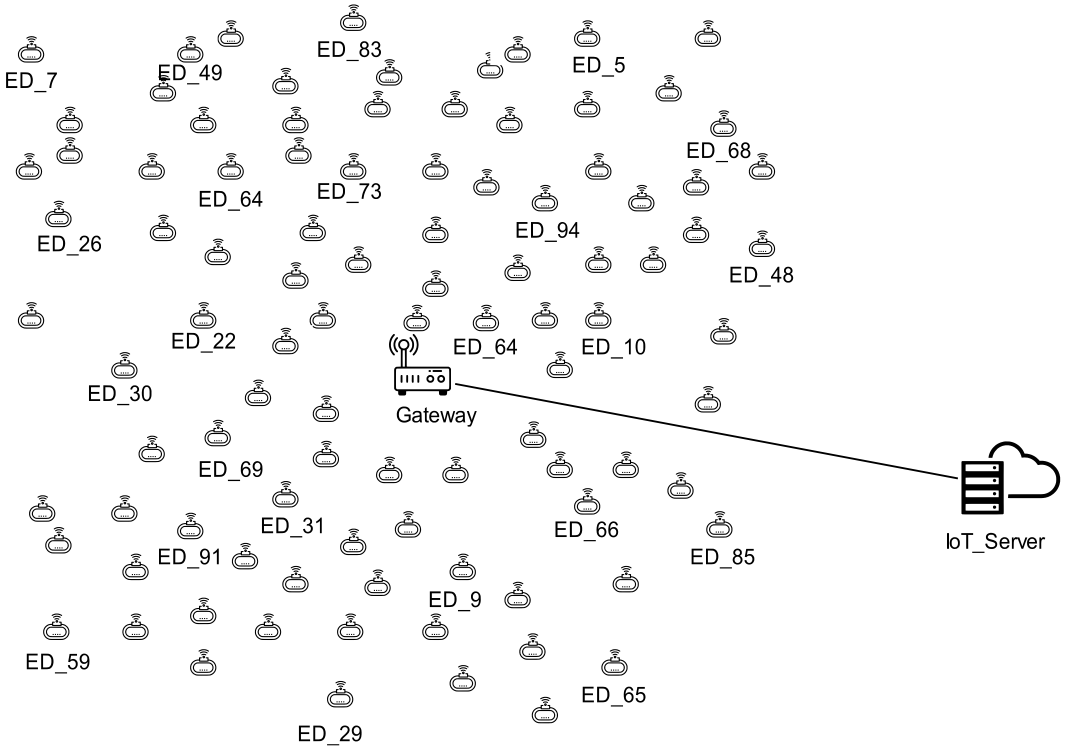


**Figure 4.1.** The LoRaWAN network scenario.

**Table 4.3.** Simulation parameters.

| **Parameter** | **Value** |
|---|---|
| Frequency | 868MHz |
| Bandwidth | 125kHz |
| Number of EDs | 100, 150, 200, 250, 300. |
| Network Radius | 5000m |
| Number of GWs | 1 |
| Number of NS | 1 |
| Payload | 20 Bytes |
| Simulation Runs | 10 |
| Simulation Time | 6.6 hours |
| App. Data Packet Rate | 1 packet per 300s, 600s, 900s, 1200s, 1500s. |

## 4.5 THE PROPOSED ADAPTIVE DATA RATE MODEL

We propose an adaptive data rate algorithm named SNR-based Spreading Factor Interference Rate controlled Adaptive Data Rate Algorithm (SSFIR-ADR). The proposed algorithm aims to decrease

**Table 4.4.** Energy model parameters.

| Parameter | Value |
|---|---|
| Initial Energy of EDs | 10000 J |
| Supply Voltage | 3.3 V |
| Stand by Current | 0.0014 A |
| Tx Current | 0.028 A |
| Sleep Current | 0.0000015 A |
| Rx Current | 0.0112 A |

energy utilisation whilst preserving a high packet delivery ratio by mitigating interference. This algorithm achieves this by dynamically controlling the allocation of spreading factors to minimise the prospect of simultaneous transmissions with the same spreading factor in a particular annulus region within the network. To facilitate this, the network is divided into K radial regions according to the available SF regions, $\mathrm{K} \in \{\mathrm{k}_7, \mathrm{k}_8, \cdots, \mathrm{k}_{12}\}$. By varying the SF values based on the defined framework, the data rate is optimised.

SSFIR-ADR is divided into two variants, SSFIR-ADR1 and SSFIR-ADR2. The key goal of the proposed algorithm is to utilise two spreading factors in a specific annulus region centred on the historical signal-to-noise ratio of individual end nodes, thereby reducing interference within that region. The SSFIR-ADR algorithm uses several global variables in determining the optimal SF allocation as defined in Algorithm 4.1.

1. The SNR values of the four most recently received data packets are stored in the ReceivedPacketList.
2. The average SNR values for each ED are computed and stored in a list, $\mathrm{SNR}_{\mathrm{avg}}$ updated every time an ED sends a packet to the network server.
3. The required SNR threshold values are stored in a list called $\mathrm{SNR}_{\mathrm{thresh}}$ as presented in Table 4.1.
4. An SF list that corresponds to the values stored in the $\mathrm{SNR}_{\mathrm{avg}}$ list is stored in SFvalue.
5. The Usageindex keeps track of the list of EDs within each SF region K which the algorithm uses to determine which EDs should have their SFs optimised.

6. Dmargin stores the value of the device margin. $\rho$ is the probability that will control the decrease of SF at region K and will provide a number from 0 to 1.
7. $\rho$SF represents a vector with the probability of EDs the algorithm randomly selects for optimization for each K region.
8. The optimised spreading factor is labelled $SF_{new}$. Once sufficient data is collected, this variable will store the new SF value computed by the algorithm.

The algorithm operates as follows: Considering each SF region K, except $k_7$, a subset of nodes within the same radial ring region K (i.e., EDs utilising the same spreading factor) is selected for transitioning to the adjacent lower SF region. Each ED is assigned the lowest SF possible such that the power received from the ED is higher than the required sensitivity threshold. SSFIR-ADR1 selects EDs that are in K with the minimum value of $SNR_{avg} > SNR_{thresh}$ and reduces the spreading factor by one. On the other hand, SSFIR-ADR2 employs a stochastic approach to randomly select a subset of end devices from the Usageindex, with a specific probability assigned for optimising their spreading factor. This subset of EDs then transitions to a new SF denoted $SF_{new}$. In our implementation for this work, we utilised a constant value of SF across all spreading factor regions. However, it is possible to set individual probability values for each of the SF levels based on the network size and node deployment considering the application needs.

The network topology with 300 EDs and its corresponding SF distribution is visualised in Figure 4.2, showcasing the differentiated SF allocations achieved by the algorithm. By incorporating these techniques, the proposed SSFIR-ADR algorithm demonstrates its ability to effectively reduce energy consumption and mitigate interference while maintaining satisfactory packet delivery performance in LoRaWAN networks.

**Algorithm 4.1** The proposed SNR-based SF Collision and Interference Reduced ADR model.

```
Require: $SF = [7,12]$, $TP = [2,14]$, $SNR_{thresh}$, $SNR_{req}$, $\rho_{SF}$
Ensure: $TP_{new}$ and $SF_{new}$ for each ED
ReceivedPacketList ← number of packets recently received
$SNR_{avg} \leftarrow$ average SNR value for ED
$SNR_{thresh} \leftarrow [-7.5, -10, -12.5, -15, -17.5, -20]$
$D_{margin} \leftarrow 10$
$\rho = rand()/RAND_{MAX}$
for each ED in the network do
    $SNR_{avg} \leftarrow avg(\text{ReceivedPacketList})$
    $SNR_{margin} \leftarrow SNR_{avg} - SNR_{thresh} - D_{margin}$
    Steps $\leftarrow floor(SNR_{margin}/3)$
    $SF = maxSF$
    while Steps $> 0$ and $SF > minSF$ do
        $SF = SF - 1$
        Steps = Steps - 1
    end while
    while Steps $> 0$ and $TP > minTP$ do
        $TP = TP - 3$
        Steps = Steps - 1
    end while
    Update UsageIndex
    for each SF in SFvalue do
        $switch(SF)$
        if $SNR_{avg} > SNR_{thresh}$ then
            if $\rho > \rho_{SF}$ then
                $SF = SF - 1$
            end if
        end if
    end for
end for
return $TP_{new}, SF_{new}$
```

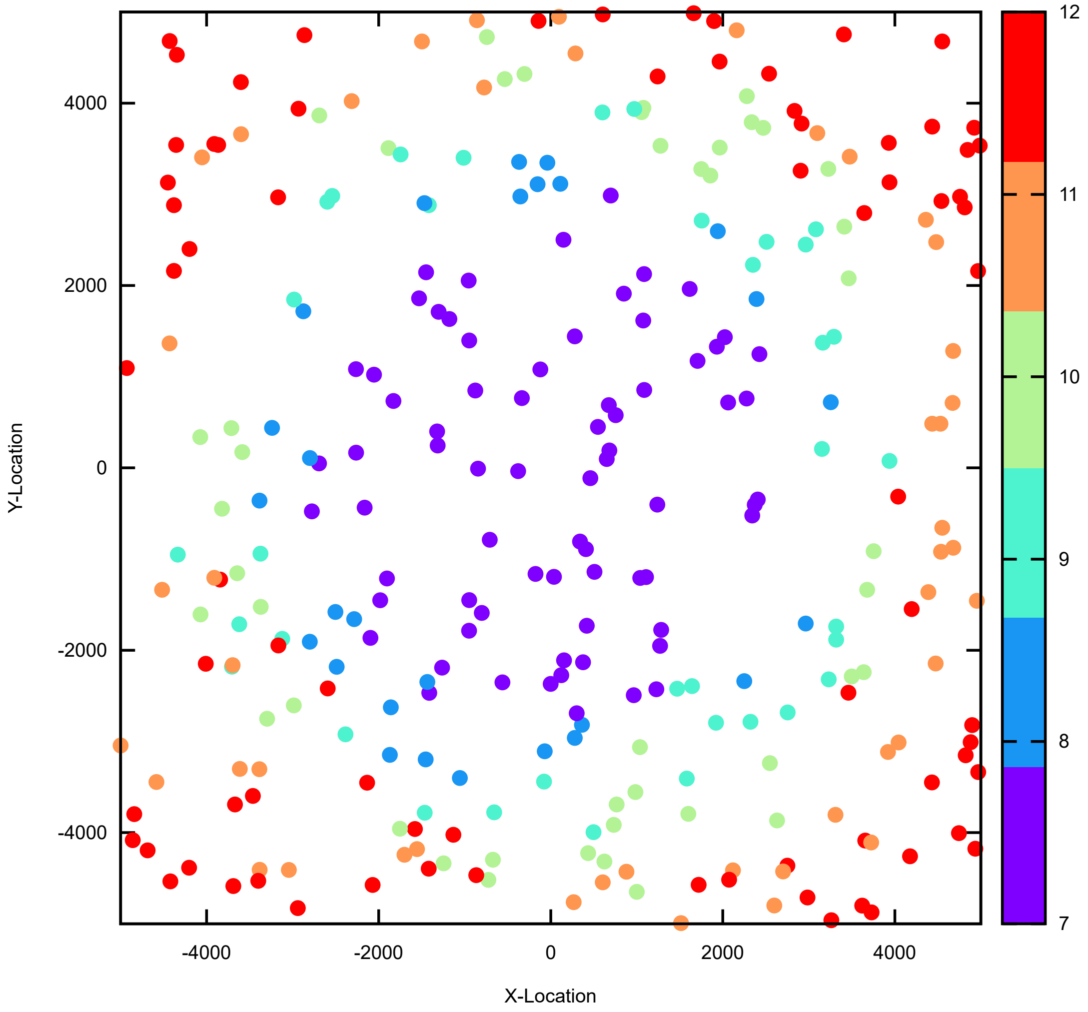


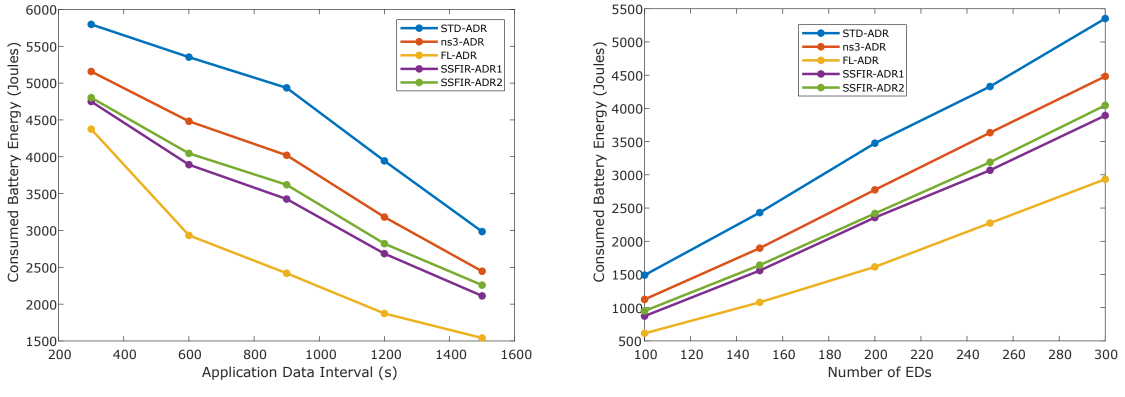
**Figure 4.2.** The SF Map –Algorithm SSFIR-ADR2.

## 4.6 RESULTS AND DISCUSSION

The obtained simulation results are graphically displayed to effectively visualise the evaluated metrics. The performance analysis of the LoRaWAN network primarily focuses on four key metrics: confirmed packet success rate (CPSR), uplink packet delivery ratio (UL-PDR), total energy consumption (ET), and interference ratio (IR). To benchmark our proposed ADR implementation, we differentiate it against the standard ADR algorithm, the ns3-ADR algorithm implemented in the ns-3 LoRaWAN module, and the fuzzy logic-based ADR scheme known as FL-ADR [94]. In the first evaluation scenario, we vary the application data packet rate while keeping the number of end devices constant at 100. In the second evaluation scenario, we vary the number of EDs while maintaining a constant application data packet rate of 600 s. The main findings of our study indicate that our proposed ADR model surpasses the standard ADR and ns3-ADR algorithms in relation to packet delivery ratio, while also demonstrating reduced interference rate and energy consumption. However, it is important to note that the FL-ADR scheme surpasses our developed framework in relation to energy utilisation and interference rate reduction, although it lags behind in achieving higher PDR.

### 4.6.1 Total energy consumption

The proposed SSFIR-ADR model exhibits a notable decrease in the global energy utilisation of the network, as illustrated in Figure 4.3(a) when considering different application data intervals, and Figure 4.3(b) when examining various node densities. When comparing SSFIR-ADR1 and SSFIR-ADR2 against the standard ADR algorithm, both variants demonstrate average energy savings of 27% and 24% respectively. It is essential to take note that the energy consumption of the ADR algorithm directly correlates with the network size, as depicted in Figure 4.3(b). Consequently, as the application data interval increases, the energy consumption decreases for a fixed number of end devices within the network. This improvement in energy efficiency can be attributed to the reduction in interference, leading to fewer collisions and subsequently fewer retransmissions. By minimising these disruptions, the proposed algorithm effectively conserves energy resources. As a result, the proposed SSFIR-ADR algorithm exhibits superior performance compared to the ns3-ADR algorithm, although it is outperformed by the FL-ADR scheme in terms of saving energy.



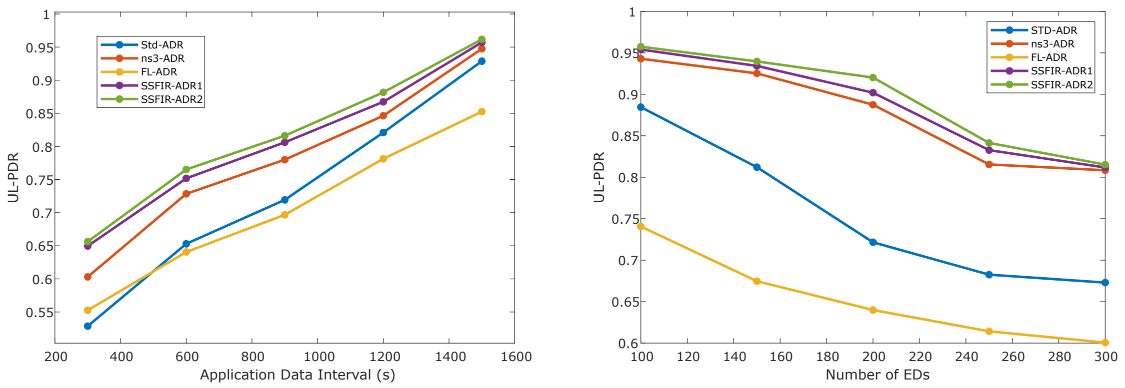
**(a)** **(b)**

**Figure 4.3.** The total energy consumption: (a) data interval vs. total consumed energy; (b) no. EDs vs. total consumed energy.

### 4.6.2 Uplink packet delivery ratio

Figures 4.4(a) and 4.4(b)) illustrate how the proposed SSFIR-ADR1 and SSFIR-ADR2 algorithms perform in terms of uplink packet delivery ratio. Both variants of SSFIR-ADR exhibit improved

UL-PDR compared to other algorithms. The primary objective of the proposed ADR algorithm is to reduce energy utilisation while preserving a high packet delivery ratio by mitigating interference and optimising data rates for end devices. However, due to the limited transmission parameters that can be adjusted by ADR in LoRaWAN, complete elimination of collisions is not feasible. As network density increases, the potential number of interferers during each transmission also rises. In this scenario, the proposed ADR algorithm surpasses all the algorithms used for comparison, highlighting its effectiveness in reducing collisions. For instance, at a network density of 200 EDs and an application data interval of 600 s, the standard ADR algorithm achieves a PDR of 0.72, the ns3-ADR algorithm achieves 0.88, the FL-ADR scheme achieves 0.64, SSFIR-ADR1 achieves 0.90, and SSFIR-ADR2 achieves 0.92. These results indicate an approximate improvement of 18% and 20% in UL-PDR compared to the standard ADR algorithm for SSFIR-ADR1 and SSFIR-ADR2, respectively. While FL-ADR outperforms SSFIR-ADR with reference to energy consumption, it falls short in achieving a comparable packet delivery ratio. This result showcases the balance between energy consumption optimisation and PDR performance.

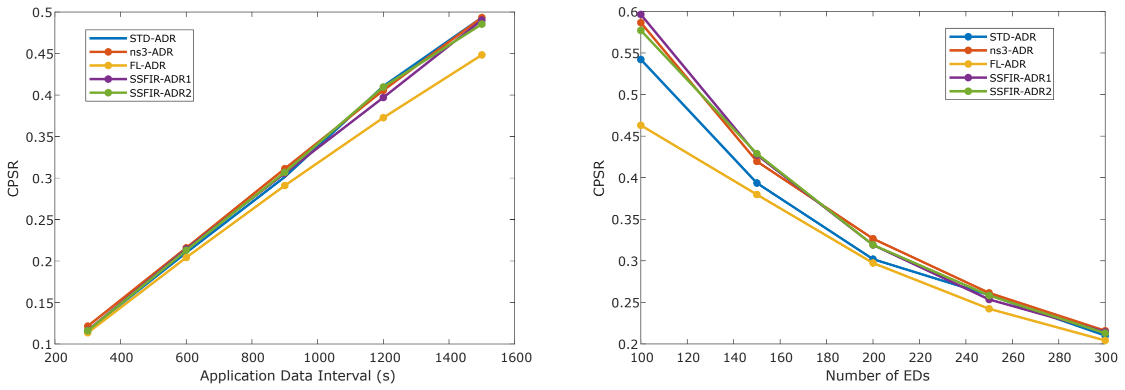


**(a)** **(b)**

**Figure 4.4.** Uplink packet delivery ratio: (a) data interval vs. uplink packet delivery ratio; (b) no. EDs vs uplink packet delivery ratio.

### 4.6.3 Confirmed packet success rate

The confirmed packet success rate (CPSR) refers to the probability of successfully receiving both the uplink and downlink packets within the available transmission attempts. Figures 4.5(a) and 4.5(b) depict the performance of the proposed SSFIR-ADR algorithm in respect of CPSR. The SSFIR-ADR algorithm demonstrates lower energy consumption in relation to the standard ADR algorithm while maintaining comparable or slightly improved CPSR. This is evidenced by the results presented in Figures 4.5(a) and 4.5(b). The reduction in interference achieved by SSFIR-ADR contributes to energy savings without compromising CPSR. It should be noted that as node density increases, CPSR tends to decrease. Conversely, CPSR increases with longer application data intervals. These trends are observed due to the higher likelihood of interference and collisions in denser networks, as well as the potential for more retransmissions with shorter data intervals. While using confirmed traffic ensures a higher level of QoS by guaranteeing accurate data reception and processing, it comes with the drawback of consuming additional airtime, limiting the number of downlinks that can be transmitted. This limitation is especially relevant when utilising a single gateway in the network. In cases where the application can accommodate unconfirmed traffic, it is advisable to opt for that approach to maximise network capacity.

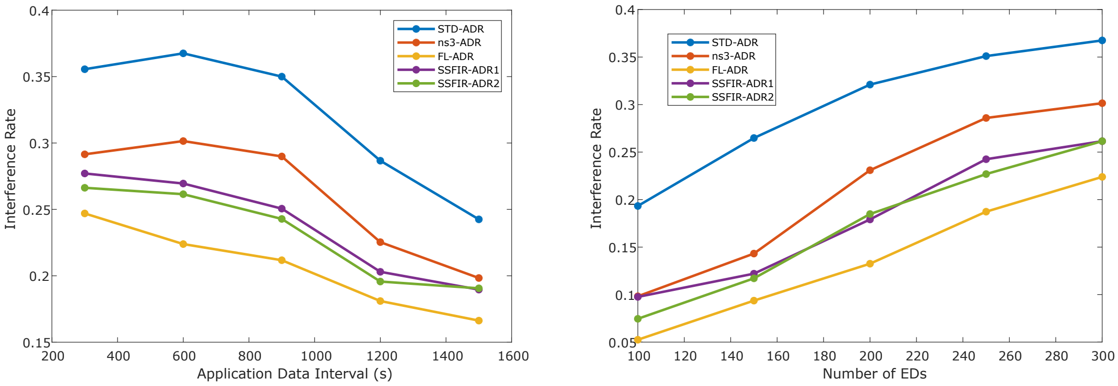


**(a)** **(b)**

**Figure 4.5.** Successful reception rate: (a) data interval vs. avg. reception rate/load; (b) no. EDs vs. reception rate/load.

### 4.6.4 Interference/collision rate

The interference or collision rate, which represents the ratio of total received packets to packets lost due to interference, serves as a measure of network performance. In Figures 4.6(a) and 4.6(b), we examine the performance of several LoRaWAN ADR implementations relating to the interference ratio. The proposed SSFIR-ADR algorithm consistently demonstrates a lower interference ratio across different application data intervals and node densities except for FL-ADR. It is worth noting that longer application data intervals generally exhibit lower interference ratios compared to faster data intervals. Both graphs in Figure 4.6 illustrate the effectiveness of the proposed SSFIR-ADR models in reducing interference ratios across all scenarios. For instance, in Figure 4.6(b), the standard ADR algorithm shows an interference rate ranging from 0.19 to 0.36 for this network with up to 300 EDs. In contrast, SSFIR-ADR2 exhibits an interference rate between 0.07 and 0.26, while SSFIR-ADR1 ranges from 0.09 to 0.26. The stochastic approach employed in our proposed model for optimising spreading factor allocation contributes to a reduction of over 20% in the interference rate in comparison with the standard ADR algorithm and 14% improvement in comparison with the ns3-ADR algorithm. However, the FL-ADR algorithm outperforms the SSFIR-ADR models by approximately 12% in terms of interference reduction. Overall, the results establish the effectiveness of the proposed SSFIR-ADR models in mitigating interference and improving network performance.



**(a)** **(b)**

**Figure 4.6.** Interference/collision rate: (a) data interval vs. interference/collision rate; (b) no. EDs vs. interference/collision rate.

## 4.7 CHAPTER SUMMARY

In this chapter, we introduced a novel adaptive data rate algorithm termed SSFIR-ADR for LoRaWAN networks, designed to increase the packet delivery ratio and decrease energy utilisation in LoRaWAN networks. The study addresses the detrimental effects of interference, which is increasingly prominent in rapidly growing IoT technologies and leads to higher packet collision rates within the LoRaWAN network. Through extensive simulations and analysis, we have evaluated the SSFIR-ADR algorithm in comparison to other ADR implementations, including the standard ADR algorithm, ns3-ADR algorithm, and FL-ADR scheme. Our findings indicate that the SSFIR-ADR algorithm achieves significant improvements in key performance metrics The obtained results highlight the superiority of our proposed solution over the standard ADR and ns3-ADR algorithms pertaining to energy consumption, packet delivery ratio, and interference rate. While the FL-ADR algorithm demonstrates superior energy consumption optimisation and interference reduction, it falls short in achieving a comparable packet delivery rate. In contrast, the SSFIR-ADR algorithm strikes a balance by achieving significant energy savings without compromising the uplink packet delivery ratio and confirmed packet success rate. The SSFIR-ADR performance is attributed to the algorithm's ability to mitigate the adverse effect of interference, resulting in fewer collisions and retransmissions. This was achieved without compromising the UL-PDR and CPSR. Our approach presents a promising option for practical LoRaWAN implementations.

# CHAPTER 5 DISCUSSION

## 5.1 CHAPTER OVERVIEW

The management of resources for the deployment of LoRa-enabled devices poses significant challenges, primarily owing to the influence of underlying propagation conditions. LoRaWAN addresses this challenge by incorporating an adaptive data rate scheme to effectively allocate device resources, including spreading factor and transmission power. Furthermore, the dynamic nature of channel conditions, link budget variations and network density make it difficult for ADR to accurately predict and respond to data rate adaptation, leading to packet loss and energy wastage. Efforts are required to explore novel techniques and approaches that can enhance resource management for LoRa-enabled devices, considering these specific challenges. By addressing these concerns, it is possible to minimise packet loss, optimise energy usage, and improve overall performance in LoRa deployments.

This thesis aimed to enhance the performance of LoRaWAN networks, by optimising the ADR scheme. The research aimed to reduce energy consumption in static end devices to extend battery life and optimise network performance. The research questions were effectively addressed, leading to the development of two novel ADR algorithms, FL-ADR and SSFIR-ADR. The reporting style employed in this thesis adheres to the fundamental principles governing the logical presentation of technical reports within the domains of electronics, computer engineering, and wireless communication networks. Notably, this concluding section of the thesis serves as a culmination, providing a concise summary of the key concepts and ideas that have been introduced throughout the study. It also highlights the significant findings and contributions made to research knowledge, as expounded upon in the preceding chapters of this thesis. This approach ensures consistency and coherence in the presentation of the research work, enabling readers to grasp the essence of the study's outcomes and impact in the field of study.

## 5.2 SUMMARY OF CHAPTERS

The research was divided into several chapters, each contributing to the overall understanding and advancement of ADR algorithms in LoRaWAN networks.

Chapter 1 provided a concise introduction to the research study, laying the groundwork for the entire investigation. The problem statement was established, aiming to identify and propose viable solutions to the investigated issues. Furthermore, the research objectives were clearly delineated, providing a definitive framework for the study. The chapter also highlighted the contributions this research makes to scientific knowledge, providing a list of potential publications that emanate from this research effort.

Chapter 2 provided a comprehensive background on LoRaWAN, performed a thorough literature review and identified research gaps in ADR schemes. It classified existing solutions based on objectives, optimisation approaches, metrics used, and computational complexity, highlighting the need for efficient solutions to improve network performance.

In Chapter 3, a novel fuzzy logic-based ADR (FL-ADR) algorithm was proposed to enhance energy efficiency, packet success rate, and interference rate. The chapter presented the system model, simulation setup, and implementation details. The chapter also included numerical and simulation results, along with a detailed discussion of the proposed algorithm's performance. Simulation results demonstrated the advantages of the FL-ADR scheme in reducing energy consumption compared to existing schemes. However, there was a trade-off with a decrease in the confirmed packet success ratio and uplink packet delivery ratio. It requires further refinement to address its impact on the confirmed packet success ratio and uplink packet delivery ratio.

Chapter 4 introduced the SNR-based Spreading Factor Interference Rate controlled ADR algorithm (SSFIR-ADR). It focused on reducing packet collision and managing interference to improve the packet delivery ratio. Through rigorous simulations and comparisons with other ADR implementations, including the standard ADR algorithm, ns3-ADR algorithm, and FL-ADR scheme, the SSFIR-ADR algorithm displayed notable advancements in key performance metrics. The performance evaluation showcased the superiority of the SSFIR-ADR algorithm over the standard ADR algorithm and ns-3ADR, highlighting noteworthy improvements in energy consumption, effectively mitigating interference and collisions while maintaining a satisfactory packet delivery ratio and energy utilisation level. The results highlighted its potential for practical implementation in LoRaWAN networks.

## 5.3 SUMMARY OF CONTRIBUTIONS

In accordance with the objectives highlighted in the introduction of this thesis, this thesis contributed to the domain of LoRaWAN networks and ADR algorithms in several ways:

1. Comprehensive review of ADR schemes: The research provided a thorough analysis of existing ADR schemes, their strengths, drawbacks, and optimisation approaches. It classified these schemes based on various factors, serving as an invaluable tool for researchers and practitioners.
2. Study of gateway and end device density: The investigation into the consequence of gateway and end node density on LoRaWAN performance helped determine the optimal number of gateways for scalability while considering energy consumption.
3. Evaluation of signal-to-noise ratio history averaging methods: The study explored different methods used in ADR algorithm implementation and their effects on network performance. It deepened the understanding of how ADR algorithms optimise network performance.
4. FL-ADR algorithm: The proposal of the fuzzy logic-based ADR algorithm offered improved energy efficiency. Although there were trade-offs in certain performance metrics, it opened avenues for further exploration and optimisation.
5. SSFIR-ADR algorithm: The introduction of the SSFIR-ADR algorithm addressed interference issues and achieved significant improvements in energy consumption and packet delivery ratio, striking a balance between performance metrics.

## 5.4 FUTURE RESEARCH OPPORTUNITIES

Looking ahead, there are several research prospects for future work. While this thesis primarily emphasises optimising energy efficiency, the optimisation of the FL-ADR algorithm to achieve improved packet success ratio and uplink delivery ratio in multi-gateway scenarios should be explored further. Additionally, further investigation and refinement of the SSFIR-ADR algorithm's parameters could lead to even more significant enhancements in interference management and energy consumption optimisation.

1. Hybrid ADR algorithms: Investigate the potential of combining the strengths of different ADR algorithms, such as the FL-ADR and SSFIR-ADR schemes, to achieve further optimisation in LoRaWAN networks.

2. Dynamic interference management: Explore adaptive interference management techniques to mitigate the adverse effects of changing environmental conditions and interference sources on network performance.
3. Machine learning approaches: Investigate the use of machine learning algorithms to enhance ADR schemes, leveraging historical data and predictive analytics for improved performance. Exploring the potential effects of integrating the Fuzzy Logic System with complementary methodologies, such as deep learning, on network performance, presents an intriguing avenue for investigation.
4. Energy harvesting and resource allocation: Explore techniques for energy harvesting and efficient resource allocation in LoRaWAN networks to maximise energy utilisation and prolong the battery lifespan of end devices.
5. Field trials and real-world implementation: Conduct field trials to validate the performance of optimised ADR algorithms in practical scenarios and identify any challenges or limitations. The practical implementation of these algorithms in real-world LoRaWAN deployments warrants consideration and validation.

By addressing these research opportunities, further advancements can be made in optimising ADR algorithms for LoRaWAN networks, contributing to the development of more efficient and reliable Internet of Things applications. In conclusion, this thesis has contributed to the understanding and improvement of ADR algorithms in LoRaWAN networks. The FL-ADR and SSFIR-ADR algorithms introduced novel approaches for energy efficiency and interference management. While there are trade-offs to consider, the research has laid the foundation for future optimisation and exploration of hybrid algorithms. By continuing to investigate these research opportunities, we can advance the performance of LoRaWAN networks, making significant strides in energy efficiency, packet delivery ratio, and interference management for IoT applications. Overall, the research presented in this thesis contributes valuable insights and innovative solutions to the domain of LoRaWAN network optimisation and ADR algorithms.

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