Towards Efficient and Scalable LoRaWAN Enabling Internet of Things

Mukarram Abduljalil Mahmood Almuhaya

Department of Computer Science

A thesis submitted in partial fulfilment of the requirements of Nottingham Trent University for the degree of

Doctor of Philosophy

February 2025

This thesis is dedicated to those who have taught me that education is the passport to the future: my parents, my wife, and my kids Tameem, Rzan, and Nooran. I hope my success today gives you happiness after all the life hardships you have endured for the sake of growing me and my nine siblings and your continued supplication. I also appreciate my wife's support and my kids' patience due to my little time with them.

Acknowledgements

”Whoever is not grateful to the people, he is not grateful to Allah”
-Prophet Muhammad (peace be upon him)

In the past three years, I have immersed myself in the scientific research field, adapting to diverse circumstances and environments. The harsh climate posed challenges, but transitioning from a conservative community to a much more open Western society proved to be even more difficult. This a personal experience highlighted the importance of resilience and the need for understanding when navigating such significant cultural shifts while keeping constant on moral values by good luck from Allah(SWT). I have been lucky to have a leader who greatly contributed to the success of my PhD study. I extend my deepest thanks to Dr. Tawfik Al-Hadhrami, the leader of my PhD journey, for his unwavering supervisory support, motivating encouragement, and wise counsel, all delivered with compassion during my study. I would also like to express my sincere gratitude to my co-supervisor, Dr. Omprakash, for his support and to Professor David Brown, who offered regular supervisory meetings, proofreading, and financial support for conferences, which was an authentic space to think out loud. Appreciation is extended to Dr. Evtim for offering valuable feedback during the annual review progress meetings.

My current self is a result of my father’s and mother’s influence. I am profoundly grateful for your sacrifices on my behalf. I also extend my gratitude to my other family members who have supported me during challenging circumstances. I would like to express my gratitude to my brother Hamzah and my cousin Omer for their support during the financial difficulties I encountered prior to commencing my PhD.

I see the PhD degree as the pinnacle of a structure. To attain this culmination, proficient builders are required at various phases of the project. I like to express my gratitude to all my educators who have instructed me at various times of my life in Yemen, Malaysia, and the United Kingdom. I like to convey my profound appreciation to AbdulKarim Abdunoor, Dr. Mohammed Alswidi, Dr. Mohammed Alradhi, Dr. Waheb Abduljabar, Zakaria Jobir and Dr. Sami Saleh for their encouragement in my pursuit of PhD studies. Your belief in my potential as an exceptional researcher was consistently present.

I like to express my gratitude to all my friends and former colleagues who have maintained contact with me, alleviating my sense of isolation. I would like to express my gratitude to my colleagues in the Computational Intelligence and Applications Research Group for the time we have spent together over the last years. I extend my gratitude to Dr. Abdullah Naser for sharing their PhD experiences with me.

Finally, I have been privileged to get academic scholarships for all my higher education degrees. I am particularly appreciative to Nottingham Trent University for providing financial support for my PhD studies via a fully-funded scholarship program. This scholarship is essential for me to attain this significant milestone in my academic career.

Mukarram Almuhaya
December 2024

Abstract

Over the past two decades, researchers in the field of wireless sensor networks (WSN) have developed an extensive array of hardware, communication protocols, operating systems, and applications to tackle the fundamental challenges posed by resource-constrained devices, limited energy supplies, and adverse Internet of Things communication requirements. Nevertheless, research on Wireless Sensor Networks has mostly focused on hardware with restricted capabilities such as Bluetooth, ZigBee, Wi-Fi. The advancement of wireless communication and embedded technology presents a new opportunity to address the persistent challenges of scaling, setting up, and sustaining a wireless sensor network (WSN). The majority of low power wide area network (LPWAN) solutions use collision-prone, uncoordinated channel access techniques to save energy. As the number of devices grows by hundreds, and thousands, this problem becomes worse due to high collisions, and LPWANs become less scalable. One-hop networks with several sensor nodes from LoRa are promising technologies due to new low-power, long-range communication and low cost. This thesis investigates the latest advancements in low-power, long-range (LoRa) wireless communication and the main issues Scalability and power consumption, quality service, reliability and approaches analysis provided.

LoRaWAN, a multi-access control protocol for LoRa, is based on the Alloa protocol, which experiences significant collision rates in big networks. This thesis presents an in-depth investigation of LoRa's performance and evaluates the unique features of LoRa, including its

spreading factors, bandwidth, transmission power, carrier activity detection, and the newly introduced multiband support. Additionally, we analyse LoRa's performance under different conditions. Using these distinctive features to construct two new enhancements to LoRaWAN, Multi-band Multi-Data rate MBMD-LoRa and Multi-Band Multi-Zone ZBMD-LoRa on the Medium Access Control (MAC) layer, both of which improve the scalability of LoRaWAN. The proposed technique enhances LoRaWAN's performance, enabling power efficiency and extending the Internet architecture to LPWANs.

In LoRa technology, packets can be received concurrently by multiple gateways. Subsequently, the network server selects the packet with the highest Receiver Signal Strength Indicator (RSSI). However, this method can lead to the exhaustion of channel availability on the gateways. The optimisation of configuration parameters to reduce collisions and enhance network throughput in multi-gateway LoRaWAN remains an unresolved challenge. This thesis introduces a novel low-complexity model for ZBMG-LoRa, categorising nodes into quarter-annulus groups called sub-zones based on their respective gateways. If the node moves to a different location, its setting will be reevaluated to obtain the setting that is suitable for that new location (subzone) in the coverage area. This categorisation allows for the implementation of optimal settings for each node's subzone, thereby facilitating effective communication and addressing the identified issue. By deriving key performance metrics (e.g., network throughput, energy efficiency, and probability of effective delivery) from configuration parameters and network size, communication reliability is maintained. Optimal transmission power configurations and spreading factors increase the throughput by more than 20% for LoRaWAN networks with multiple gateways.

The performance of the physical(PHY) and MAC layers of LoRaWAN was analysed, and the mechanism that controls the adaptive data rate was also taken into consideration. In this investigation, it was discovered that the rate of data extraction among devices was unfair, with the devices that were closest to the gateway and those that used high data rates being given preference. The performance decays further when some devices use their energy sooner than others, owing to the disparate allocation of spreading factors, hence reducing the network's lifetime. In the final work package, this thesis proposed a novel fair frame scheduling method for allocating service functions to nodes in six parallel frames distributed in a timely manner on six frequency band channels with the objective of minimising total data collection time while adhering to radio duty cycle constraints. The result shows that fair frame FF-LoRa minimises the length of longer frame (time a round) to 25% approximately, which makes the farthest device more power efficient and leads to enhancement of the network lifespan.

Contents

Nomenclature

Technical Acronyms

LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
TDMA	Time Division Multiple Access
ADR	ADaptive Data Rate
PDR	Packet Delivery Ratio
PDR	Packet Error Ratio
CR	Code Rate
FC	Frequency Channel
CF	Carrier Frequency
ISM	Industrial Science Medical
CRC	Cycle Redundancy Check
SF	Spreading Factor
BW	Bandwidth
TP	Transmission Power
ToA	Time On Air
TS	Time Slot
SNR	Signal to Noise Ratio
RSSI	Received Signal Strength Indicator
QoS	Quality of Service
SDR	Slim Data Rate
MBMD	Multi-Band Multi-Data Rate
MBMz	Multi-Band Multi-Zone
ZBMG	Zone-Based Multi-Gateway
GT	Guard Time

Mathematical Acronyms

f	Spreading Factor
b	Bandwidth
T_{air}	Time On Air
R_b	Bite Rate
cr	Code Rate
PL	PayLoad (Data Size
$Tsack$	Time Slot for Acknowledgment
S	Sensitivity
SNR	Signal to Noise Ratio
NF	Noise Factor
T_{sym}	Time of Symbol
P_{rx}	Receiver Power
P_{tx}	Transmission Power
G_{tx}	Transmission Gain
L_{tx}	Transmission Loss
Lpl	Loss of Direction
L_m	Miscellaneous Loss
$\mathrm{G}_r x$	Receiver Gain
L_{rx}	Receiver Loss
d	Distance
d_0	Distance reference
λ	Path loss exponent
X_σ	Variance to account shadowing
β_f	Number of Nodes which configure with SF f
ζ_f	The Maximum Number of Nodes which configure with SF f
α_b	Number of Nodes which configure with Bandwidth b
α_g	Number of Nodes which under the coverage area of Gateway g
E_b	Energy per Bite

List of Figures

List of Tables

Chapter 1

Introduction

The Internet has revolutionised lifestyle and business practices in recent years. The availability of an extensive and continuously expanding information pool at any time and place has accelerated innovation and learning processes, revealed new aspects of creative work, and simplified routine tasks such as selecting travel routes or shopping through minimal effort. The Internet is generating opportunities previously deemed unimaginable, exemplified by the emergence of multi-billion dollar companies lacking material assets, including Google, Facebook, Amazon, Uber, Netflix, and PayPal.

A significant paradigm shift has emerged from the Internet: the Internet of Things (IoT). IoT is designed to facilitate connections among objects via the Internet, extending beyond human interactions. "Things" refer to any conceivable device, encompassing sensors, home appliances (such as toothbrushes, coffee makers, irons, dishwashers, etc.), phones, wearables, actuators, traffic signals, and smart toys, among others. In early 2020, 9.5 billion devices were connected to the Internet, with projections indicating an increase to 28 billion by 2025, as estimated by IoT Analytics [2].

Devices associated with the IoT generally require the transmission of minimal data, including temperature, humidity, pressure values, or positional coordinates. IoT devices often require the wireless transmission of limited data volumes. The increasing connectivity of devices to the IoT is attributed to the extensive array of beneficial applications it offers. Applications encompass industrial and environmental sensing, energy and smart grid systems, smart metering, agricultural monitoring, health monitoring, localising and tracking, transportation, and smart city initiatives. Devices in low-power wide-area networks (LPWANs) must autonomously transmit over extended distances and sustain operation for several years[3]. Consequently, the implementation of very low-power wireless transmission protocols is necessary. Many low-power transmission protocols utilise uncoordinated channel access schemes, exemplified by the ALOHA protocol [4].

The extensive range of applications entails a variety of wireless connectivity requirements. The IoT standards environment is notably diverse [5]. Bluetooth Low Energy (BLE) [6], ZigBee [7], and 802.15.4 [8]are the primary standards in short-range wireless connectivity. These technologies offer a single-hop coverage area, which can be expanded through multi-hop relaying of data within a mesh network, resulting in a high-cost network. Many IoT applications necessitate a form of direct long-range wireless connectivity. LPWANs can be categorised into two primary types: licensed LPWANs, such as cellular IoT, and unlicensed LPWANs. The primary shared characteristic of the two categories is their extensive coverage area, spanning several kilometres in urban settings and extending to tens of kilometres in rural environments [9].

Cellular IoT standards, including Narrow Band NB-IoT, represent an advancement of the current 3rd Generation Partnership Project (3GPP) cellular standards. Cellular IoT technologies possess complex physical (PHY) and medium access control (MAC) layers. Cellular IoT standards encompass various use cases and utilise licensed frequency bands to ensure robustness and security. Cellular standards, originally designed for high data rate services catering to a limited number of devices, now encounter the challenge of transitioning to low data rate services that accommodate a significantly larger number of devices, IoT communication categories illustrated in Figure 1.1.

Conversely, unlicensed LPWAN technologies do not represent an advancement of any pre-existing standard. The PHY and MAC layers of unlicensed LPWAN technologies have been specifically developed for the IoT, resulting in a relatively straightforward design. Examples of unlicensed technologies include Sigfox, Weightless, Ingenu, and LoRa. These technologies

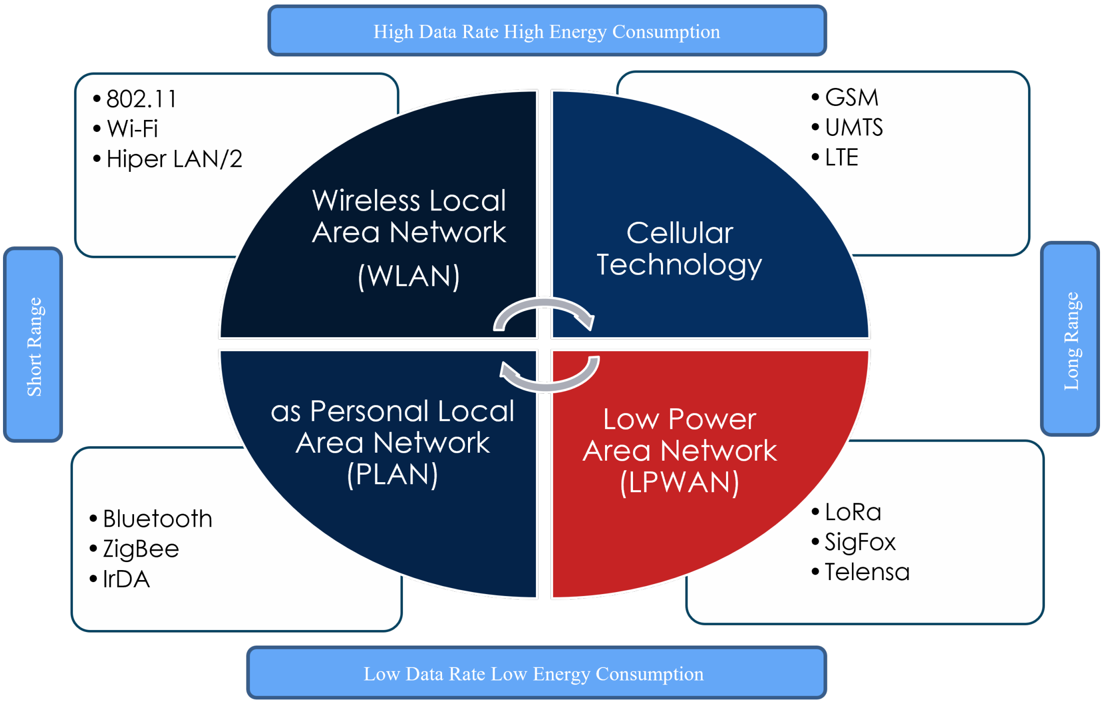


Figure 1.1: Internet of Things communications Technologies

utilise the unlicensed industrial, scientific, and medical (ISM) bands. Consequently, their operational and infrastructure costs are lower than those of cellular IoT. Unlicensed LPWANs employ uncoordinated MAC layer schemes for energy efficiency, unlike the centralised MAC protocols utilised in cellular IoT.

Uncoordinated MAC protocols are founded on either the ALOHA scheme or listen-before-talk (LBT) schemes. Channel access mechanisms are typically selected for networks characterised by a substantial and fluctuating number of connected devices exhibiting unpredictable traffic patterns. In pure ALOHA, each device initiates packet transmission upon the generation of a new message. The end-node devices may request acknowledgements (ACKs) based on the application requirements. A retransmission may be attempted if a packet is not positively acknowledged. The absence of coordination in pure ALOHA channel access schemes results in diminished network throughput, primarily due to packet collisions as the number of connected devices increases. A significant number of retransmission attempts can diminish energy efficiency [10]. To address the challenges posed by the growing number of connected devices, LPWAN standards often impose limitations on the maximum permissible transmission time for each device, commonly referred to as duty-cycle restrictions. Slotted ALOHA segments time into defined slots based on Time Division Multiple Access (TDMA), permitting each device to initiate packet transmission solely at the commencement of each slot. Slotted ALOHA requires a form of time synchronisation, typically accomplished through the periodic transmission of beacons. Thus, slotted Aloha consume more energy than pure Aloha. Low-power networks effectively employ pure ALOHA, the most power-efficient channel access method available.

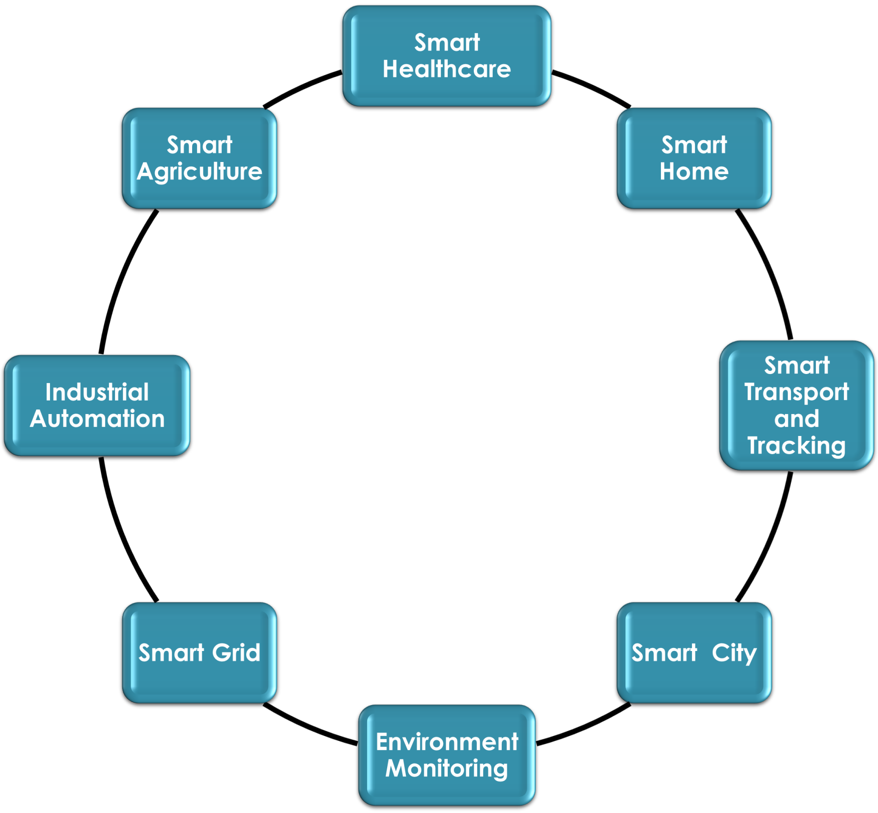


Figure 1.2: LoRa Applications

1.1 Overview on LoRa/LoRaWAN

This thesis investigates the Long Range Wide Area Network (LoRaWAN) protocol, a widely utilised unlicensed LPWAN technology. LoRaWAN, along with its physical layer known as Long Range (LoRa), employs spread-spectrum modulation to facilitate long-range connectivity and enhance resistance to noise and interference. Research on LoRaWAN includes several essential research domains that are vital for enhancing network performance and progressing IoT applications. LoRaWAN studies mostly focus on network multi-hop, multi-gateways and optimisation, with scholars aiming to improve the efficiency and scalability of LoRaWAN networks. This necessitates the creation of sophisticated routing algorithms, adaptive data rate techniques, and congestion management methods to optimise network capacity, reduce interference, and guarantee uninterrupted data transmission. It is required to enhance network throughput, reduce latency, and improve the overall performance of LoRaWAN installations, hence facilitating robust and dependable IoT connections.

Alongside network optimisation, research in LoRaWAN focuses on enhancing energy efficiency and optimising devices to extend the battery life of IoT devices and reduce power usage. Novel strategies have been evaluated to improve energy efficiency in data transmission, establish effective sleep modes, and study energy harvesting methods to prolong device functionality in resource-limited settings [11, 12]. Studies aim to enhance the energy efficiency of LoRaWAN devices to promote sustainability, extend operational life, and provide seamless connections for IoT applications across various sectors, hence advancing sustainable and efficient IoT deployments.

Additionally, the studies in the field of LoRaWAN focus on scalability and dependability to tackle the issues of accommodating many devices and assuring dependable communication under diverse environmental circumstances. Researchers examine strategies for network densification, interference reduction, and reliability improvements to augment the scalability and robustness of LoRaWAN networks [13][14]. It is essential to boost scalability and dependability to facilitate the seamless integration of many IoT devices, optimise resource utilisation, and improve the overall resilience of LoRaWAN installations, hence enabling large-scale IoT solutions across various domains [15].

Moreover, investigations in the domain of LoRaWAN include facilitating applications that require frequent data transfer. Research focuses on enhancing LoRaWAN networks to effectively manage applications requiring periodic data transfer, such as frequent sensor data reporting. Researchers investigate methods to guarantee prompt and dependable transmission of periodic data, reduce energy expenditure during idle intervals, and enhance network resources to meet the distinct needs of periodic applications[16]. This facilitates the smooth integration of various IoT use cases within LoRaWAN networks.

1.2 Motivation and Research Problem Statement

Investigating LoRa technology offers a fascinating opportunity to explore novel wireless communication solutions that facilitate long-range connection with little power consumption and operate on unlicensed frequency bands, which is crucial for many IoT applications as illstrated in the Figure 1.2. LoRa provides scalable, cost-effective network solutions spanning industries such as smart cities, agriculture, and industrial IoT, capable of transforming processes and enhancing efficiency. Exploring LoRa research facilitates the development of significant real-world solutions in environmental monitoring and infrastructure management while also offering interdisciplinary career advancement opportunities that enhance expertise in wireless communication technologies and IoT systems, contributing to the progression of network optimisation techniques. This research aims to achieve notable advancements for universities, business, and extensive research initiatives.

LoRaWAN, despite its widespread applicability, is characterised by unregulated medium access, which results in insufficient guarantees for high packet delivery rates. This limitation notably affects its feasibility for various use cases that require brief data collection intervals, such as smart agriculture, intelligent monitoring or Industrial Internet of Things (IIoT) applications[17].

Consequently, it is imperative to investigate TDMA protocols as a more reliable alternative to LoRaWAN. This exploration should emphasise the key considerations, challenges, and perspectives pertinent to the design of time-slotted protocols that integrate LoRa at the physical layer. Furthermore, priority should be given to protocols that either possess proof-of-concept implementations or have been successfully deployed in real-world environments.

The ALOHA algorithm encounters significant congestion under high traffic conditions and exhibits inefficiency as network size increases. A network utilising Pure ALOHA typically achieves approximately 18.39% of its maximum efficiency, while a Slotted-ALOHA network can attain around 37% of its potential efficiency [18],[19]. Recent studies have demonstrated that the LoRaWAN Class A system specification has inherent scalability limitations resulting from the ALOHA-like characteristics present in its MAC layer. In response to these limitations, LoRaWAN incorporates an Adaptive Data Rate (ADR) scheme that dynamically optimises airtime, data rate, and energy consumption efficiency. Despite that, many studies have found that ADR still suffers from high collisions and overhead and energy efficiency due to the frequent adjustment of ADR[20].Therefore, more investigation for recent studies is necessary to be a base for our solution.

LoRaWAN has become the most widely used LPWAN solution due to its physical layer design and regulatory advantages because LoRaWAN has a broad communication range, and some projects install more gateways to distribute the network load between the gateways to enhance the packet deliver ratio (PDR). However, coverage of the gateways might overlap cite RN1362. In LoRa technology, packets can be received simultaneously by multiple gateways. Then, the network server selects the packet with a high receiver signal strength indicator(RSSI) only. Thus, this behaviour exhausts the channels' availability on gateways [21],[14]. The optimisation of configuration parameter settings to minimise collision and maximise network throughput in multi-gateway LoRaWAN remains an unresolved matter [22]. This thesis proposes a novel low-complexity model for zone-based multi-gateway ZBMG-LoRa, which categorises nodes into distinct categories according to the zones of Gateway (GW) with optimal settings for each node subzone to communicate effectively and address this issue.

Time Slot (TS) LoRa effectively eliminates packet collisions, enhancing network scalability and data transmission reliability. However, the additional energy costs for synchronisation pose a significant challenge [23]. The transmission cost of one packet from a node configured with Spreading Factor(SF) 12 is equivalent to the cost of transmitting seven packets from nodes configured with SF9 and 23 packets from a nearby node configured with SF7. This configuration leads to an unfair distribution of power consumption among the nodes, which may result in a rapid and gradual decline in the overall lifespan of the network[24],[25]. To improve fairness in data rates and energy consumption among end devices, It should be consider signal parameters such as Received Signal Strength Indicator (RSSI), spreading factor, and bandwidth with frequency channel allocation. Adjusting transmission power during time slot scheduling can help achieve equitable energy use among all nodes, regardless of their distance from the gateway, ensuring fair data extraction [26, 27].

1.3 Research Questions and Objectives

This thesis investigates the network stack of Low Power Wide Area Network (LPWAN) technologies, with a particular focus on LoRaWAN, across various scenarios to evaluate their advantages and disadvantages in supporting Internet of Things (IoT) applications.

1.3.1 Research Questions

- What are the most effective parameters of LoRa technology?
- What are the most effective and recent solutions to optimise the Adaptive Data Rate algorithm in LoRaWAN-based IoT deployments regarding throughput, scalability and energy efficiency?
- What are the most effective and recent solutions TDMA (time slot-based) to enhance LoRaWAN IoT deployments regarding data rate, scalability and energy efficiency?

1.3.2 Research Objectives

The aim is to propose enhancements that improve performance and broaden application domains while taking into account existing network limitations. The primary emphasis of the research is on resource management, scalability, and energy efficiency, which have been inadequately addressed in the context of LoRaWAN. This thesis has the following aims and research objectives :

- To investigate the most effective LoRa parameters, the common solutions and the latest studies which tried to improve LoRaWAN protocol and study their advantages and drawbacks with a comprehensive comparison.
- To enhance LoRaWAN network scalability to thousands of devices by allocating appropriate settings for each end node, utilising a slim data rate and minimising the Packet transmission time.
- To propose an algorithm for LoRaWAN to mitigate the collisions through optimize channel utilisation in the multi-gateway networks by selecting the adequate parameter settings (RSSI, PLos, SF, TP) using a new technique based on the ZBMG-LoRa technique for the LoRa network.
- To design a Fair Frame (FF-LoRa) scheme based on the time slot LoRa and ADR approach for increasing the LoRaWAN network lifespan, a more scalable and reliable network for periodic IoT applications.
- To evaluate the effectiveness performance of the proposed techniques under various LoRaWAN simulation scenarios using the LoRaSim simulator compared with the conventional schemes in terms of scalability, PDR, energy consumption, and throughput.

1.4 Original Contributions

This thesis makes a significant contribution to the existing body of research on LoRaWAN and efficient IoT by introducing novel methods and simulation model results about scale LoRa networks with minimum energy consumption to coordinate with most LPWAN network applications. Specifically, it is outlined in the following key contributions:

C1:) A comprehensive analysis of top TDMA methods, including LoRaWAN-based time slot frames. A complete comparison of Time Slot systems, including their performance in time slot frame design, acknowledgements, problems, and considerations while constructing a time slot frame (Chapter 3).

C2:) MBMD-LoRa and MBMZ-LoRa are diverse allocations for spreading factors within the multiband frequency, improving the in-transmission data rate and making the packet smaller. This serves to prevent node collisions, hence leading to energy conservation by eliminating the need for packet retransmission, which enhances the scalability of LoRaWAN (Chapter 4).

C3:) A two-step algorithm to significantly improve the scalability and reliability of LoRaWAN networks with multiple gateways (chapter 5).

C4:) A novel fair frame technique (FF-LoRa) effectively minimises maximum frame time and enhances power efficiency for the most distant devices, thereby extending both the device and network lifespan (Chapter 6).

1.5 Publications

As a result of the research presented in this thesis, the following publications have been published:

Mukarram A.M.Almuhaya,Tawfik Al-Hadhrami,Omprakash Kaiwartya , David J. Brown. ”A Comprehensive Comparison in Time-Slotted Frame Protocols in LoRaWAN IoT Technology.” IEEE Smart World Congress 2023 was held in Portsmouth, UK on 28th-31st, August, 2023,**C1**.

Mukarram A.M.Almuhaya,Tawfik Al-Hadhrami,Omprakash Kaiwartya , David J. Brown. ” MBMD-LoRa Scalable LoRaWAN for Internet of Things: A Multi-Band Multi-Data Rate Approach.” 16th International Conference on

Computational Collective Intelligence 9-11 September 2024, Leipzig, Germany(Springer),**C2**

Mukarram A.M.Almuhaya,Tawfik Al-Hadhrami,Omprakash Kaiwartya , David J. Brown. "A Novel Fair Frame Time Slot LoRaWAN Internet of Things." The 3rd International Conference on Intelligent Computing and Next Generation Networks Conference Bangkok, Thailand (IEEE 2024),**C4**

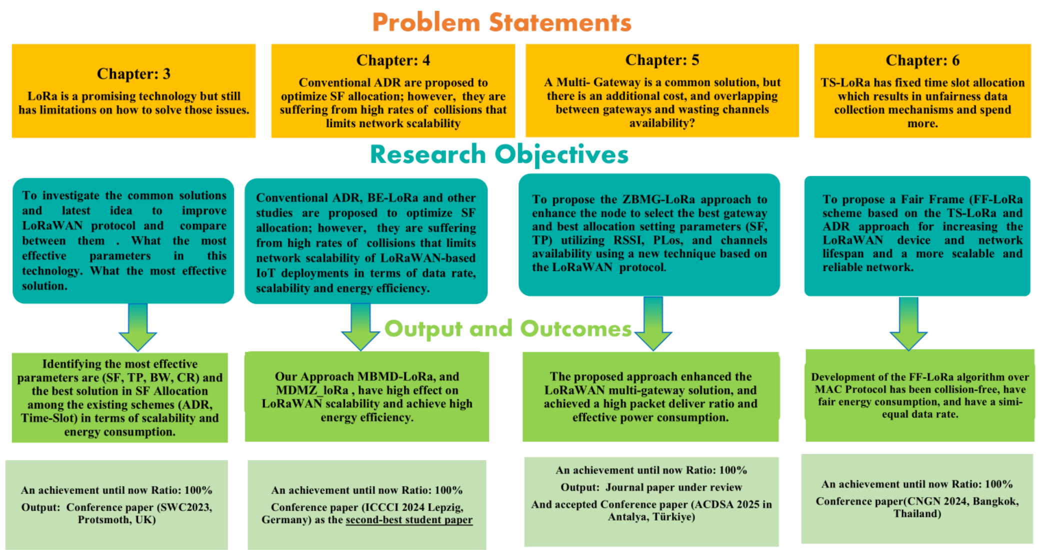


Figure 1.3: Thesis Summary

1.6 Thesis Outline

This thesis consists of seven chapters. The organisation of the thesis structure is further illustrated in Figure 1.3. The contents of this thesis are summarised as follows:

Chapter 2: This chapter outlines key details regarding LPWANs, with a particular focus on LoRa. Analyse the most significant parameters in LoRa, such as spreading factor and bandwidth, carrier frequency, and time on air. Moreover, the LoRaWAN architecture network, the network layer system in LoRaWAN, and an operation mode of LoRaWAN will be mentioned frequently throughout this thesis.

Chapter 3: This chapter provides a comprehensive literature review of LoRa as an innovative technology within the context of IoT communications. A substantial body of research has been thoroughly reviewed, analyzed, and evaluated, encompassing a wide variety of methods and techniques designed to improve the ADR and TDMA mechanism in LoRaWAN. This chapter explores the factors and challenges involved in developing LoRa network protocols for time-slotted medium access. The chapter reviews various time-slotted solutions described in the literature, focusing on open-source protocols that have been validated through reliable simulators and extensive real-world testing. Moreover, it highlights key considerations for creating LoRa network protocols for time-slotted medium access, including details on joining methods, scheduling algorithms, synchronisations, and acknowledgement slots, among other aspects. The comparison has been done across multiple indicators, ranging from acknowledgment processes to scalability.

Chapter 4: This Chapter presents an analysis of the PHY Layer and MAC layers of LoRaWAN, as well as the suggested protocol for resource allocation, with the goal of achieving a high data transmission rate in LoRaWAN. Additionally, simulation results are shown in this chapter to demonstrate the benefits of the suggested protocol in comparison to the current literature in terms of collision probability, throughput, and energy consumption. Each of these advantages is discussed in detail.

Chapter 5: This chapter outlines enhancement MAC protocol, which, along with new resource allocation protocols utilising multiple gateways, can potentially enable scalable and reliable data collection applications. In addition, it presents comprehensive simulation results demonstrating the performance of these proposals in comparison to current leading solutions and the standard LoRaWAN.

Chapter 6: This chapter outlines the proposed new design for Fair Frame MAC protocol founded on TDMA. In conjunction with new resource allocation protocols that prioritise parallel scheduling and synchronisation, this approach is designed to minimise data collection time. Such advancements aim to enhance device power efficiency and prolong network longevity, thereby supporting a range of unique applications. Additionally, this chapter includes extensive simulation results that illustrate the performance of the proposed methods in comparison to existing literature and standard LoRaWAN protocols.

Chapter 7: This chapter presents the conclusions arising from the thesis and suggests directions for future work on the LoRaWAN protocol.

Chapter 2

Background

2.1 Introduction

This chapter thoroughly examines LoRa and LoRaWAN, concentrating on the physical layer and the MAC layer, respectively. It discusses the transmission parameters associated with LoRa technology, analysing the impact of each parameter on communication between the LoRa device and the LoRa gateway. Additionally, it investigates the correlation between these parameters and the transmission time of the LoRa packet, providing detailed insights into the packet structure.

Moreover, the Chapter addresses the various operational modes of LoRa, specifically Class A, Class B, and Class C. The strategies for connecting and registering the LoRa device and the LoRa gateway are also outlined.

The chapter ultimately concludes with a summary of the key findings and insights.

2.2 Low Power Wide Area Network

Different low-power wide-area network (LPWAN) systems come with different technical specifications, economic models, and approaches to implementation [28]. There are two broad classes of LPWAN systems that may be defined by their spectrum. To begin, the licensed spectrum is used by the third-generation partnership project (3GPP)-standardized narrowband IoT (NB-IoT) and long-term evolution for machines (LTE-M). The implementation of sophisticated protocols linked to high energy consumption and increasing prices is necessary for these technologies to provide high data rates and bandwidth while ensuring quality-of-service (QoS)[29],[30]. Additionally, the unlicensed spectrum is being used by the SigFox and LoRaWAN protocols, which are in a race to construct their networks first. This second group of devices allows for low-power, long-range communication by sending a tiny signal across a wider frequency spectrum, which increases resistance to interference from other systems. Nevertheless, this approach squanders the shared spectrum and often runs into serious self-interference issues, which restricts the overall network capacity [31]. Based on LTE, the aforementioned LPWAN technologies, such as NB-IoT and LTE-M, increase the capacity of cells and lengthen the range of devices, allowing for the transmission or reception of tiny amounts of data over a small BW.

Traditional LTE-based solutions, on the other hand, are expensive due to factors such as the high deployment costs, complicated protocols needed to control device operation, and the devices' high power consumption[32]. IoT systems that use LTE-M may extend the life of a battery by as much as ten years because of the minimal power consumption of LTE-M nodes. Using 1.08 MHz BW, which is the same as six LTE physical resource blocks, LTE-M devices function. One reason LTE-M is more affordable than 2G, 3G, and 4G is because it simplifies IoT end devices (EDs) [33].
One such LPWAN technology that relies on LTE is the NB-IoT, which was developed by 3GPP and released in Release 13. Figure 2.1 shows a brief comparison between LTE-M, NB-IoT and EC-GSM. While it does meet the necessary criteria to lower device prices and restrict battery use, its innovative air interface sets it apart from other LTE standards. As a result, NB-IoT cannot perform several functions that are available in LTE, such as handover, channel quality management, carrier aggregation, dual connection, and more. NB-IoT can be used in three different modes: in-band, guard band, and stand-alone. When operating independently, the GSM frequency ranges from 10 kHz to 200 kHz, with a bandwidth of 200 kHz. Both in-band and guard-band

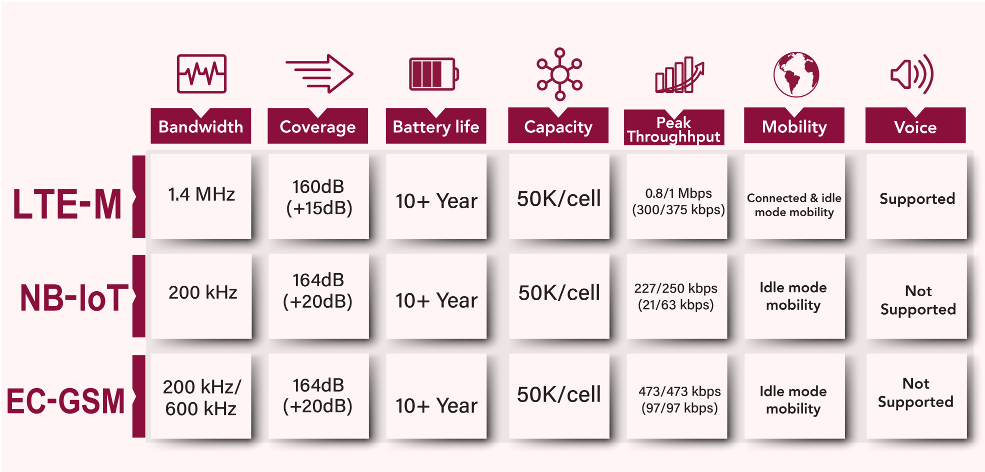


Figure 2.1: IoT Technologies and Features

modes of operation take advantage of the newly introduced LTE resource block. Low latency and great service quality are the primary goals of the NB-IoT, which mainly seeks to increase indoor coverage and facilitate connection between many low-throughput devices [34]. A second kind of LPWAN technology is SigFox and LoRa technologies are part of the unlicensed spectrum. SigFox operates on the 20 kHz BW ISM band, with either 868 or 915 MHz serving as the core frequency, depending on the region in question. Using the ISM band means that LoRa EDs must have their transmission time (TX) limited by a duty-cycle constraint. The frequency spectrum used for TX and local restrictions determines the duty cycle, which might be 0.1%, 1%, or 10%. According to the research community in this area, efficient LoRaWANs should have a duty cycle lower than 1% [35], which aligns with the constraints placed by the European community on duty cycles. The time that EDs may spend transmitting is constrained because of the restrictions placed on utilising ISM bands. LoRa Overcome SigFox regarding variable packet size, Multi-band frequency, fixability, and self-deployment. Therefore, this thesis title focuses on LoRaWAN due to the advantages of LoRa's Physical Layer.

2.3 LoRa/Physical Layer

The LoRa system offers significant processing advantages for improved link budgets and resilience to multipath and interference. It is a patented technique of Chirp Spread Spectrum (CSS) modulation that incorporates a Forward Error Correction (FEC) mechanism [36]. The unlicensed sub-GHz ISM radio band is where LoRa operates; in Europe, this is between 863 and 870 MHz, whereas in the US, it's at 902 MHz and 928 MHz. It also abides by duty cycle constraints, which are as low as 1% in certain locations around the world. LoRa's long-range transmission and low power consumption are particularly impressive when compared to those of short-range wireless protocols and cellular technologies. With a range of up to 15 kilometres in rural regions and 5 kilometres in urban areas, a battery life of up to 10 years per device, and a data rate of 0.3 to 37.5 kilobits per second [37], it is a strong contender in the wireless communications market. Compared to other wireless signals, LoRa is less likely to experience fading and more resistant to interference and intra-interference, to the Doppler effect [38]. Its devices are inexpensive, and gateways can receive many signals at once. LoRa networks in the real world seldom achieve optimal performance due to implementation complexity and varied interference.

2.3.1 LoRa Modulation

A chirp is defined as a sinusoidal signal characterized by a frequency that either increases or decreases over time, often expressed through a polynomial function that delineates the relationship between time and frequency[36]. Chirp spread spectrum transmission utilizes a bandwidth that is considerably wider than what is necessary for the specified data rate [39]. This method is categorized under the direct-sequence spread spectrum (DSSS), which leverages controlled frequency diversity to recover data from weak signals. In comparison to narrowband transmissions, DSSS mitigates the constraints related to the receiver's sensitivity and robustness, thereby enhancing the communication range; however, this improvement occurs at the expense of a diminished data rate. Consequently, DSSS is particularly well-aligned with the requirements of IoT networks. Within DSSS, data is disseminated in a sequential manner, whereas CSS modulation accomplishes the spreading effect through a carrier frequency that varies continuously over time. LoRa signal waveforms are characterised by bandwidth, spreading factor, and carrier frequency, as outlined in the introduction.

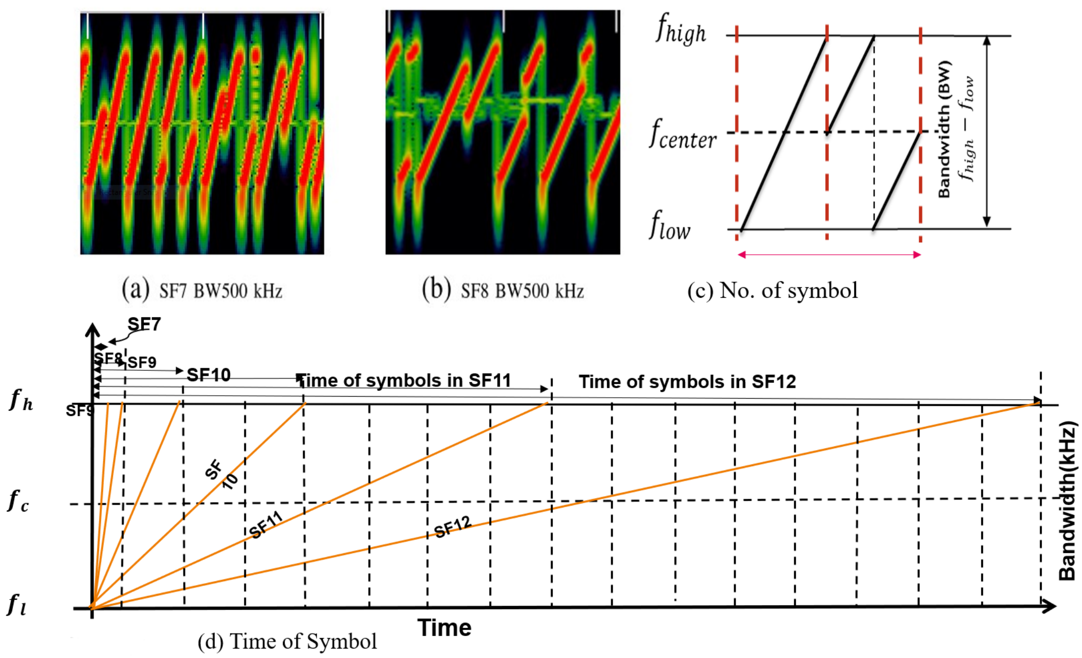


Figure 2.2: Chirp Spread Spectrum

2.3.2 LoRa Transmission Parameter

LoRa comprises five transmission parameters: Carrier Frequency, Transmission Power, Spreading Factor, Bandwidth, and Coding Rate. The values of these parameters determine data rate, transmission range, energy consumption, and resilience to noise and narrowband interference. The subsequent sections describe these parameters, primarily referencing documentation for the Semtech SX1272, while also being applicable to other sub-1 GHz LoRa radio transceivers.

- **Spreading Factor**

  The Spreading Factor (SF) represents the ratio of the symbol rate to the chip rate. An increased spreading factor enhances the Signal-to-Noise

Ratio (SNR), thereby improving sensitivity and range; however, it also results in greater airtime for the packet. The calculation of chips per symbol is determined as 2SF. For an SF of 12 (SF12), 4096 chips per symbol are utilised[40], and Figure 2.2 illustrate the deference. Each increment in SF results in a halving of the transmission rate, thereby doubling the transmission duration and, consequently, the energy consumption. The spreading factor may be chosen from the range of 6 to 12. SF6, possessing the highest transmission rate, represents a unique case that necessitates particular considerations. This mode is infrequently utilised in practice, as the receiving side must be aware of the coding rate and packet size in advance. Radio communications utilising distinct spreading factors exhibit orthogonality, enabling network separation through the application of varying SFs.

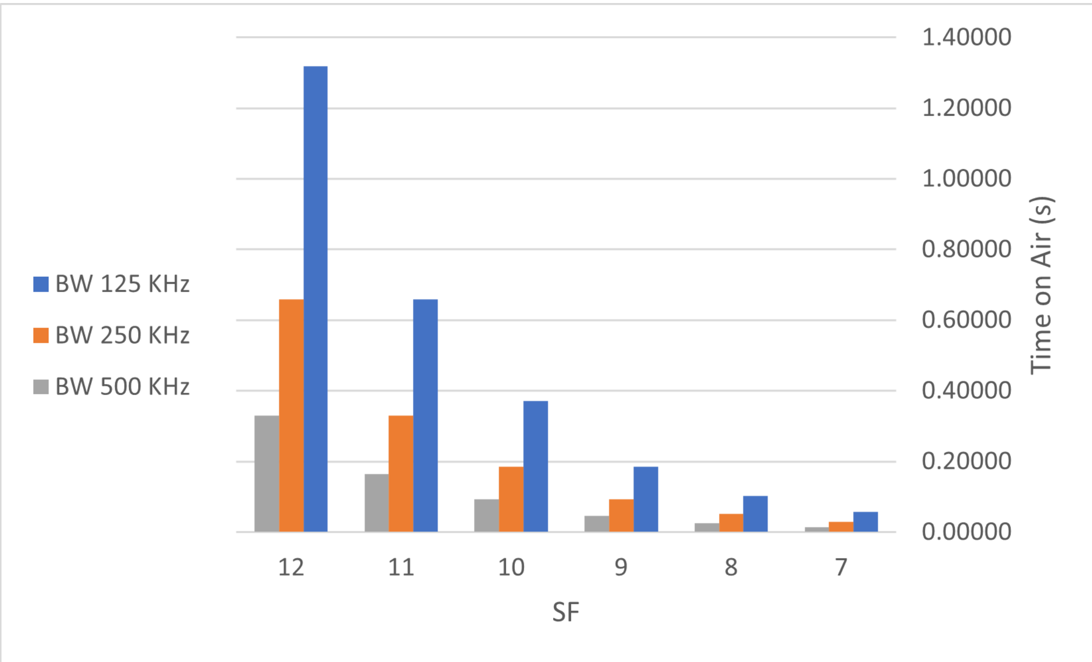


Figure 2.3: Bandwidth Impact on Time on Air

- **Bandwidth**

  The Bandwidth (BW) refers to the spectrum of frequencies within a given

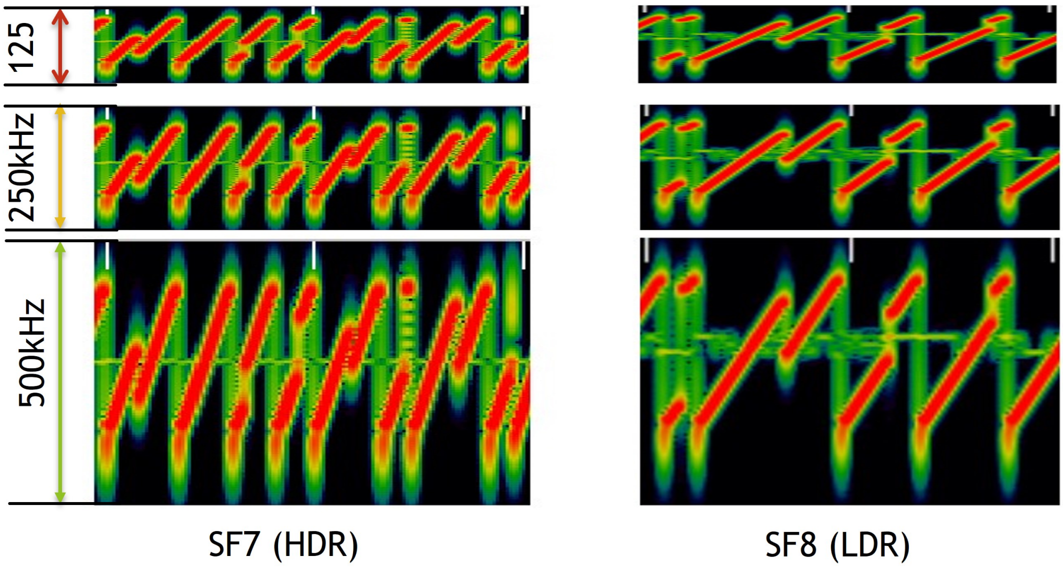


Figure 2.4: Bandwidth Impact on Time on Air

transmission band. A higher bandwidth results in an increased data rate, leading to reduced transmission time; however, it also causes a decrease in sensitivity due to the incorporation of additional noise. A lower bandwidth results in increased sensitivity but decreased data rate. A reduced bandwidth necessitates more precise crystals, with fewer parts per million (ppm) tolerances. Data is transmitted at a chip rate that corresponds to the bandwidth. A bandwidth of 125 kHz is equivalent to a chip rate of 125 kc/s. The SX1272 features three programmable bandwidth settings: 500 kHz, 250 kHz, and 125 kHz, designated as BW500, BW250, and BW125, respectively. Advanced LoRa radios, such as the Semtech SX1276, can be programmed within a frequency range of 7.8 kHz to 500 kHz.

- **Code Rate**

  The Coding Rate (CR) represents the Forward Error Correction (FEC) rate utilised by the LoRa modem, providing a safeguard against bursts of interference. An elevated CR provides enhanced protection, yet prolongs airtime. Radios with varying CR, while maintaining the same CF, SF, and

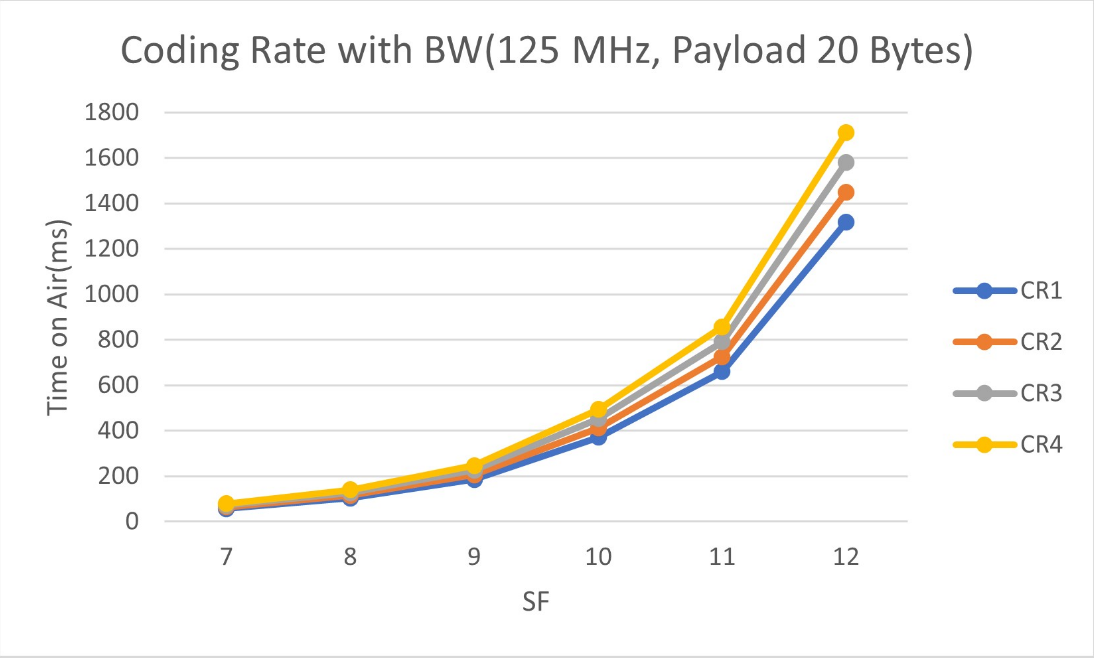


Figure 2.5: Coding Rate Impact on Time on Air

BW, can communicate effectively, provided that packets are transmitted with explicit headers. CR can be chosen from 1 to 4 (CR1 to CR4), which corresponds to an FEC rate of 4/(CR + 4). The CR of the payload is contained in the packet header, consistently encoded at 4/8.

- **Carrier Frequency**

  Carrier Frequency (CF) refers to the central frequency utilised within the transmission band. A standard LoRa radio functions within the sub-1 GHz frequency range, specifically adjustable from 137 MHz to 1020 MHz, with programmability in increments of 61 Hz. The operating range is frequently constrained to the local ISM bands, contingent upon regional requirements. Recent LoRa radio chips, such as the Semtech SX1280, function within the 2.4 GHz ISM band, which offers broader accessibility in comparison to the sub-1 GHz band.

- **Transmission Power**

  LoRa can adjust the Transmission Power by a factor of one dB, from -4 dBm to 20 dBm. Because the LoRa radio chips often only have one antenna output, the range is typically restricted to between 2 dBm and 20 dBm. This is because the LoRa radio chips typically have both a low-power and a high-power antenna output. In addition, power levels that are more than 17 dBm need the use of specialised handling techniques, the modification of the settings for the over-current protection, and the standard recommendation of a duty cycle of 1%.

2.3.3 Signal Noise Ratio

The signal-to-noise ratio (SNR) is a critical element in LoRa communication as it indicates the power relationship between the transmitted signal and the ambient noise. An augmentation in the signal-to-noise ratio of LoRa systems leads to improved reliability, an extension of the communication range, and the ability to support higher data rates. Furthermore, the signal-to-noise ratio directly influences signal demodulation, affects link budget calculations, and underscores the importance of antenna quality and optimal placement. Improving the SNR in LoRa necessitates strategic actions, including noise mitigation, antenna optimisation, and power management. Conversely, real-time monitoring and testing are crucial for sustaining and enhancing network performance in LoRa-based IoT applications. Table 2.1 presents the SNR values according to each spreading factor.

2.3.4 Receiver's Sensitivity

The minimum signal power level detectable by a receiver is termed the receiver's sensitivity in LoRa communication. This sensitivity is crucial for both range and reliability. Enhanced sensitivity could increase communication range, enhance coverage, and enable higher data rates. Enhancements may be achieved by the use of high-quality antennas, low-noise amplifiers, and effective filtering. It also influences link budgets and the compromises between performance and interference.

Table 2.1: Receiver Sensitivity and SNR for SF

SF	Bit Rate (kbps)	Receiver Sensitivity (dBm)	SNR Threshold (dB)
7	5.47	-123	-6
8	3.13	-126	-9
9	1.76	-129	-12
10	0.98	-132	-15
11	0.54	-133	-17.5
12	0.29	-136	-20

2.3.5 LoRa Packet Structure

The format of a LoRa packet is shown in Figure 2.6 - described in more detail in references [41][42]. The five components of a LoRa packet are the following: the preamble, the physical (PHY) header, the PHY payload, and the cyclic redundancy check (CRC) for the payload, which is optional.

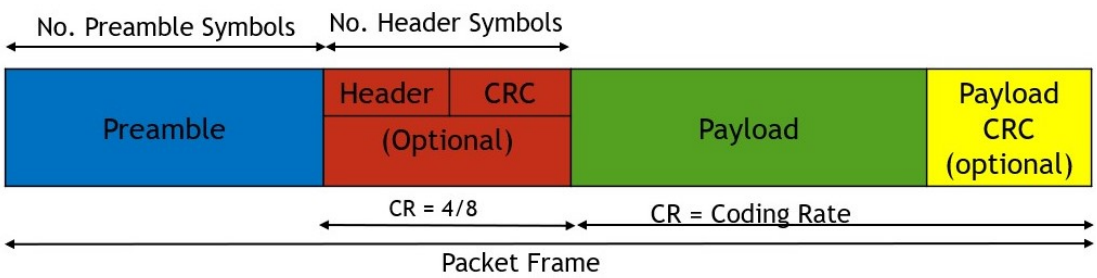


Figure 2.6: LoRaWAN Packet Formate

- **Preamble**

  To enable packet synchronisation and frequency offset estimates, the first part of a LoRa packet is the preamble. The preamble comprises a programmable portion consisting of N_{pr} upchirps alongside a fixed sequence that includes two network identifier symbols and two and a quarter downchirps.

- **Header**

  An optional header is part of the packet that transmits important information such as the coding rate, the number of bytes in the packet, whether or not the payload has a CRC, and a checksum for the bits in the header. When the header is not present, as in implicit header mode, the receiver settings must be configured explicitly. A detailed explanation of the header structure can be found in references [41][43], and the relevant illustration is provided in Figure 2.6.

- **Payload and CRC**

  The main segment of the packet is known as the PHY payload. This section is crucial as it can contain either data packets, which carry user information, or MAC layer control packets that manage network communications. The payload has a maximum allowable size of 255 bytes, allowing for a range of data delivery. Additionally, following the payload bits, there is an option to include a 16-bit cyclic redundancy check for error detection, ensuring data integrity during transmission.

2.4 LoRaWAN MAC Layer

Above the LoRa physical layer, LoRaWAN's simple MAC layer is based on an open-source protocol developed by the LoRa Alliance. The first version is thoroughly detailed in [44], whereas the revised current version is in [45]. This section succinctly introduces the LoRaWAN network architecture and outline the fundamental characteristics of the LoRaWAN MAC layer to elucidate how the LoRaWAN channel access scheme influences network throughput and the role of PHY layer characteristics in this context.

2.4.1 LoRaWAN Network Architecture

The architecture of the LoRaWAN network is shown in Figure 2.7. Numerous LoRa end nodes deliver data wirelessly to the LoRa gateways. LoRaWAN employs a star architecture, whereby end nodes may send information only via centralised gateways rather than directly to one another. The gateways facilitate the receiving of LoRa packets and the demodulation of data; however, they possess no further intelligence.

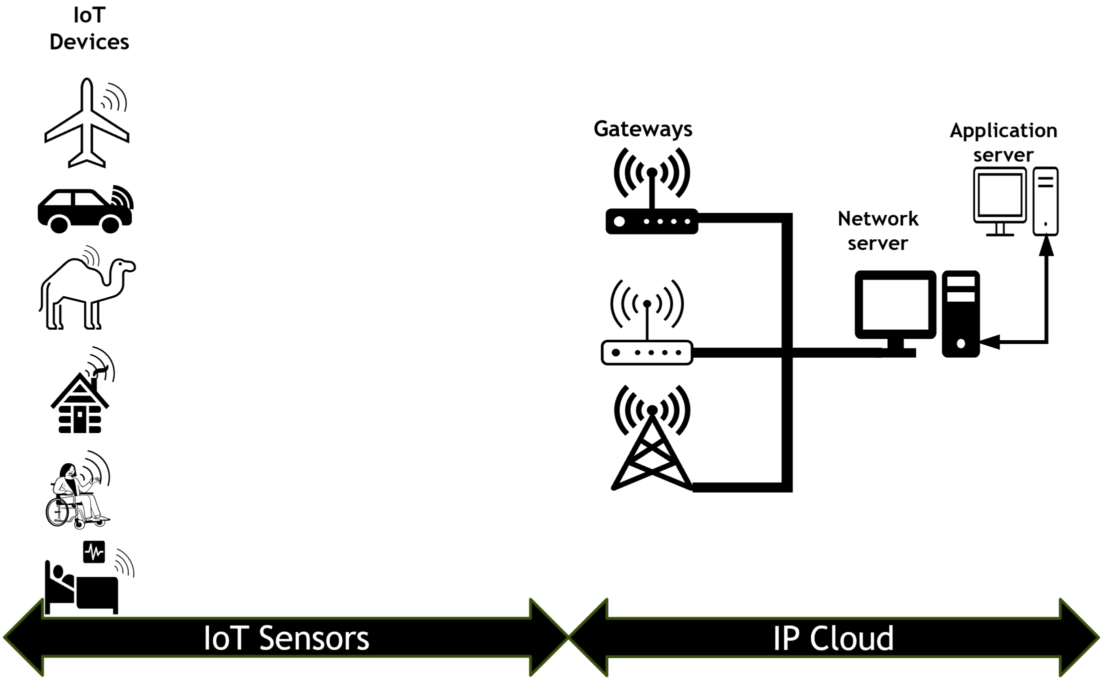


Figure 2.7: Network Architecture

As their primary function is to mediate communication between the network server and the wireless transmission, they only transmit the raw data. The real brains of the system, the network server, are located on the other end; they use the inherent variation to their advantage by aggregating receptions from several gateways, which means that the same packet might reach the server via numerous paths. The network server also arranges the end nodes' downlink packets, which may include MAC instructions and acknowledgements (ACKs) (but only for validated uplink traffic). Many applications may connect to the same network server if other organisations, such as The Things Network (TTN) [46], run the application servers.

2.4.2 LoRaWAN Classes of Devices

LoRaWAN has three categories of devices: Class A, Class B, and Class C. This section concisely outlines the primary attributes of each class.

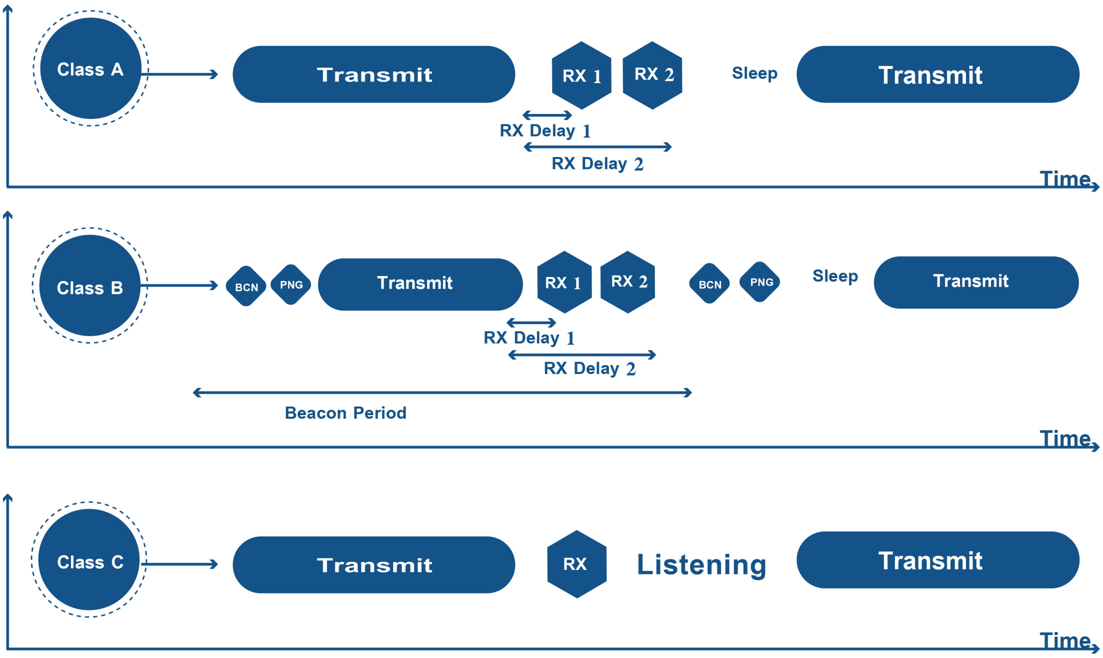


Figure 2.8: Operation Mode of LoRaWAN

- **Class A**

  All end-node devices fall under this category. According to [45, 46], Class A characteristics are absolutely necessary for LoRaWAN end nodes, hence Class B and Class C devices should include them. Class A end nodes have the capability to exclusively initiate communications using the ALOHA protocol, which means they use the least amount of power [47]. Consequently, the end-node radio is often off, saving power for the next packet transmission (Unconfirmed or confirmed uplink traffic). To reduce congestion, LoRaWAN guidelines recommend using confirmed uplink traffic only when required since a gateway cannot accept uplink packets from end nodes while broadcasting downlink packets. A gateway-to-end node downlink communication requires an uplink transmission and a reception window (Rx1) 1s after the uplink broadcast. The downstream message in window Rx1 uses the same frequency band, BW, and SF as the uplink transmission. If a downlink message is not received during the initial transmission, the end node must activate a second reception window (Rx2) 2 seconds after the conclusion of the uplink transmission, utilising a specified frequency band along with a designated bandwidth B and spreading factor SF. Default settings are region-specific, but MAC commands allow the Network Server (NS) to change them. The default settings for Rx2 in Europe consist of a carrier frequency of 869.525 MHz, a bandwidth of around 125 kHz, and a maximum spreading factor of about 12 [48]. Every time an end node sends an uplink message without confirmation, it must also open the receive windows so the network server has a chance to send data.

- **Class B**

  Class B devices are identical to Class A devices in every way, except that they may take programmed downlink messages and open reception windows (called ping slots) at regular intervals. Each node at the end of the network needs its own exact timing that is in sync with the server. To ensure that all nodes at the end of the network are in sync with one another, the gateways periodically broadcast beacons on the downlink. Even though they may run on batteries, Class B gadgets need more electricity than Class A devices use.

- **Class C** The most power-hungry devices in this category cannot function without an external power supply. Class C end nodes aim to constantly scan for downlink messages by utilising the Rx2 window settings of Class A devices, with the exception of when an uplink message is being sent or the short Rx1 window that follows an uplink message [47].

2.4.3 Joining Procedure

New EDs are required to complete an activation procedure to join and authenticate with the LoRaWAN network. During this activation procedure, two session keys are exchanged between the EDs and the NS. The LoRaWAN protocol offers two activation modes. The first method is Over-The-Air Activation (OTAA), and the second method is activation by personalisation [44]. The joining procedure in OTAA occurs between the EDs and the NS to facilitate participation in the data communication process. This process involves the exchange of join requests and join accept messages. The process is initiated by ED, which sends a joining request to NS that includes *devEUI*, *AppEUI*, and a *DevNonce*. LoRaWAN employs this mechanism to discard certain joining requests with similar *DevNonces*, thereby enabling the system to detect potential replay attacks. Upon successful receipt of the join request by the join server, a join accept message will be dispatched to the ED, containing the newly generated *JoinNonce*. The join server will generate the Application session key (AppSKey) and Network session keys (NwkSKeys) using the previously provided request message fields and *JoinNonce*, thereby facilitating device access to LoRaWAN services [49]. The Application session key will encrypt data transferred by the EDs, while the network session key will assure integrity. Be advised that these keys will be dynamically allocated to EDs during each joining procedure, hence enhancing network security and adding complexity to the joining process. Nonetheless, participation in the activation by personalisation process is unnecessary, since the *AppSKey* and *NwkSKeys* are immutable and pre-stored on the end devices. The application and network keys are immutable throughout the activation session. This procedure simplifies the join process and reduces the number of exchanged messages required to enter the network, compromising the LoRaWAN network's security level.

2.4.4 LoRaWAN Channel Access

Channel access planning in LoRaWAN is a multifaceted task that requires careful consideration due to the need for end devices to conserve battery power, along with duty cycle limitations that restrict the number of re-synchronization messages sent from the gateway to these devices. Each sensor has the capacity to transmit data whenever it is available, though current implementations do not incorporate channel sensing or collision avoidance strategies. Since the foundational study on LoRaWAN channel access by Bankov et al. [50], numerous innovative approaches have been explored. Various authors have contributed valuable insights into LoRaWAN planning [51], [52] and methods focused on loss reduction and improved decoding [53], [54]. Additionally, Beltramelli et al. [10] have effectively summarized a range of alternative solutions for channel access, thereby paving the way for future advancements in this area.

- **Pure Aloha**

  LoRaWAN employs a modified ALOHA protocol that operates without synchronisation for channel access [52]. End devices are capable of transmitting data whenever it is available, which may result in numerous message collisions. As a result, the maximum channel capacity that can be utilised is 18.6% in a pure Aloha system [55]. Related work has proposed various alternative channel access approaches, including Slotted ALOHA, Listen Before Talk (LBT), and Scheduled MAC, as discussed below.

- **Slotted Aloha**

  Slotted ALOHA represents a potential enhancement for channel access [55]. The system partitions available channels into time slots, facilitating channel access through slot allocation. End devices are permitted to initiate transmissions only at the commencement of a slot. This configuration theoretically enables slotted ALOHA to decrease collisions and the vulnerable time by 50% relative to random access [56]. The maximum channel utilisation has been increased to 36.8% [57]. Accurate timing and re-synchronization are essential for maintaining device alignment with time slots, necessitating consideration of clock inaccuracies. Additionally, significant variances in the transmission Time of Arrival (ToA) constrain the effectiveness of slotted ALOHA [18].

- **Listen Before Talk**

  A distinct strategy involves listening prior to speaking. Ortin et al. investigate this in conjunction with ALOHA [58] and independently [59]. The devices monitor the channel prior to initiating a transmission and transmit solely when the channel is unoccupied. The interference among devices in a network with numerous end devices attempting simultaneous transmission can be mitigated by employing a listen-before-talk strategy; however, performance is constrained by the hidden node problem. The performance of listen before talk diminishes to the level of pure ALOHA when all nodes in a network are concealed from one another [10]. Many nodes may remain concealed from others due to the extensive range of LoRa transmissions [10].

- **Scheduled MAC**

  Unlike slotted ALOHA, in a LoRaWAN, each device is required to register for a transmission slot at the gateway through a time-scheduled method. Once a slot is assigned, a sensor is restricted to utilising only its designated slot for transmissions. This concept suggests that message collisions and data loss can be entirely prevented. Random clock drifts or delays may occur in practice with low-cost LoRa sensors [55]. This hinders optimal time-scheduled channel access in actual deployments. Literature indicates that common clock drifts vary from 0.5 ppm to 100 ppm [60], with 1 ppm corresponding to a drift of 3.6 ms per hour. The performance of time-scheduled channel access is contingent upon the availability of slots and the appropriateness of slot lengths in relation to the transmission time of messages. However, variations in LoRa-specific transmission parameters, the transmitted payload, and the spreading factor result in differing times of arrival for LoRa messages. Additionally, due to the necessity for the gateway to adhere to LoRaWAN duty cycle regulations, re-synchronizing each sensor's clock after every transmission is unfeasible. This issue was solved by adding Guard Time (GT) - more details in chapter 3.

2.4.5 Adaptive Data Rate Mechanism

The LoRaWAN adaptive data rate (ADR) mechanism manages the fundamental trade-off between data rate and communication range. The ADR mechanism optimises the network's throughput and extends the life of the battery by adjusting the spreading factor, coding rate, and transmission power of nodes. Understanding the performance characteristics of the underlying physical layer is necessary for the ADR mechanism, even though it is located inside the MAC layer. In order to choose the target error rate using a physical layer model, the ADR mechanism as described in this thesis - makes use of channel state information, namely the SNR. This procedure allows for the determination of a suitable data rate and the modification of transmission parameters in accordance with the given SNR.

The ADR mechanism operates in both the end node and the network server. Each end node has the option to permit the network server to manage the ADR mechanism or to manage it independently. The ADR algorithm implemented on the end node is defined by the LoRa Alliance [47], while the network operator may determine the algorithm utilised on the network server. The ADR algorithm on the network server is capable of adjusting both the spreading factor and the transmission power, whereas the ADR algorithm on the end node is limited to increasing the SF following unsuccessf ul packet delivery attempts.

By setting the downlink-ADR bit to one during a downlink transmission, the network server tells the end node when it may manage the spreading factor and transmission power of a device. By setting the uplink-ADR bit to one during an uplink transmission, an end node may inform the network server to limit the spreading factor and transmit power. According to the LoRaWAN standards, end nodes are encouraged to choose the network server that will handle the ADR mechanism whenever possible [61]. For example, if the network server is unable to handle the ADR mechanism because of sudden changes in channel characteristics, it will set the downlink-ADR bit to zero. It is advised that in this case, a mobile end node should use its own ADR mechanism and set the uplink-ADR bit to zero. It is advised that a stationary end node keep the uplink-ADR bit set to one until the network server reactivates the ADR mechanism.

2.4.6 LoRaWAN Security

LoRaWAN offers services such as media access, ADR and security. End devices can begin transmitting as soon as they wake up in LoRaWAN since the MAC layer uses a basic ALOHA MAC protocol [58] that doesnot need channel detection or time synchronization. In addition, ADR is a crucial mechanism of LoRaWAN since it enables end devices to be set with varying data rates on the fly in response to changes in the network. There have been various investigations since LoRaWAN does provide an ADR algorithm [62]. LoRaWAN's security features include data encryption, message integrity checking, and node authentication, and these features are implemented using two separate 128-bit session keys generated using Advanced Encryption Standard (AES) algorithms (i.e. NwkSKey and AppSKey). In order to get the session keys, two approaches can be adopted: Over-the-Air Activation (OTA) and Activation by Personalization (ABP) (OTAA)[63].

2.4.7 Time Division Multiple Access

Through the usage of TDMA protocols, many nodes are able to use the same transmission channel within different time slots while still using the same frequency for transmission. This eliminates the possibility of collisions occurring. They also eliminate the energy loss that comes with over-listening to the channel or listening to it while doing nothing, which is another reason why they are so popular. For instance, Rizzi et al. [64] used the Time Slotted Channel Hopping (TSCH) approach with the Time Division Multiple Access (TDMA) technique in order to improve the throughput and dependability of the network. On the other hand, the synchronisation technique is no longer present. A technique for on-demand TDMA was suggested by Piyare et al. [65]. This technique makes use of low-energy wake-up radios to enable unicast and broadcast modes for node triggering and time slot allocation, respectively. Gu et al. [58] developed a TDMA-based LoRa multi-channel transmission control system that incorporates an urgent ALOHA channel and negative acknowledgement (ACK) to facilitate one-hop out-of-band control for wireless sensor networks.

The primary issue in TDMA MAC studies is the scheduling and allocation of time slots. Haxhibeqiri. et al. [66] utilised the network synchronisation and scheduling entity (NSSE) as the primary scheduler for the LoRaWAN network to manage transmission scheduling. Specifically, the node transmits a request that includes the traffic periodicity to the NSSE and receives a response detailing the allocated time slots, which are encoded in a probabilistic space-efficient data structure. Some nodes may share the same slot with a certain probability, resulting in collisions. Abdelfadeel et al. [3] proposed a fine-grained scheduling scheme called FREE. Specifically, nodes are assigned corresponding transmission parameters, including SF, TP, and time slot, and then execute bulk data transmission within the predetermined time slot. However, FREE addresses the collision issue but does not achieve real-time gearbox. Leonardi et al. [67] introduced RT-LoRa, a new LoRa MAC protocol designed as an alternative to LoRaWAN, capable of supporting real-time low transmission. In RT-LoRa, the duration of time slots is constrained by the minimum packet size, establishing a lower bound, and varies with different spreading factors. Zorbas et al.[23] proposed TS-LoRa, a self-organising time-slotted communication approach that computes a hash algorithm to map the assigned addresses of nodes into unique slot numbers, instead of depending on a centralised scheduler for time slot allocation. Furthermore, the dynamic positioning of floating nodes results in signal strength degradation and increased packet errors when compared to nodes that are statically deployed on the ground, attributable to the antenna's polarisation and directivity. Wang et al. [68] introduced an attitude-aware link model and a channel access method called PolarTracker. This method utilises the node's attitude alignment state to schedule transmissions during optimal alignment periods, thereby enhancing link quality.

To find the best primary studies on time slot LoRaWAN deployment in the vast IoT, we combed through the available literature and picked, evaluated, and analysed them all. Chapter 3 used the Prisma methodology to conduct a systematic literature review to choose which research papers to include. As a preliminary step, the articles are organized into categories then, deep reading and content analysis to distinguish between the chosen papers was conducted - more details in Chapter 3.

2.4.8 LoRaWAN Versions

As a result of the recent development in resource-constrained IoT devices, many versions of LoRaWAN have been produced in order to improve its performance in terms of security, scalability, and real-time long-range communication. A stable version of LoRaWAN, version 1.0, was made available to the public in the year 2015 [69]. The LoRa Alliance made a few small adjustments to the standard during the course of the subsequent years in order to meet the ever-increasing demand for communication systems that are based on the LoRa protocol. However, there are two versions that are considered to be the most important: LoRaWAN v1.0.3 [45] and LoRaWAN v1.0.1[70]. In July of 2018, the most current version of LoRaWAN, version 1.0.3, was published. This version addresses some of the issues that were present in its predecessors, LoRaWAN versions 1.0.1 and 1.0.2, and it also overcomes some of the performance constraints that were present in LoRaWAN version 1.1 [71]. Not only does it give support for class B devices, but it also includes several MAC commands that may be used as a replacement for beacon timing requests and responses. LoRaWAN version 1.0.1, which was released in October 2017, was designed to circumvent some security flaws that were present in earlier versions, such as weak keys encryption and management.

Additionally, it was designed to provide support for various solutions to the most common LoRaWAN security attacks, which include packet alteration, eavesdropping, and ACK spoofing. In addition to this, it provides handover roaming for IoT devices that are resource-constrained and powered by batteries. In version 1.0.4, the Algeria channel plan has been substantially revised, incorporating EU868 support, involvement before, modifying band references for South Africa limiting. Bolivia's support to AS923 bands, allowing single-channel gateways with channel hopping, synchronising downlink channel selection for US915 and AU915 with the capacity to add channels. Adjusting channel requirements to align with certain global standards, deprecating CN779, specifying certain PHY parameters, establishing global CFList definitions, withdrawing EU868 support from specific areas [1]. Adding relay specification support, acknowledging band usage in the Australian economic zone, and identifying Class B beacon formats across all LoRa modulation spreading factors[1]. The LR1121 is a highly efficient, multiband transceiver that facilitates metropolitan ISM band communications in the sub-GHz and worldwide 2.4GHz frequency, in addition to S-Band capability for satellite connection [72]. The LR1121 facilitates LPWAN applications by supporting

LoRa and (G)FSK modulation on sub-GHz and 2.4GHz bands, Sigfox modulation on sub-GHz bands, and Long Range Frequency Hopping Spread Spectrum (LR-FHSS) on sub-GHz, 1.9-2.1GHz Satellite, and 2.4GHz ISM bands[72].

2.5 Summary

Initially, the chapter underscores the significance of low-power wide-area networks (LPWANs) in the IoT ecosystem and explores a range of relevant technologies, including NB-IoT, ZigBee, LTE-M, SigFox, and LoRa. Subsequently, it elaborates on the structural framework of the LoRa network, examining LoRa as a physical layer. It also identifies key factors and variables that substantially influence the enhancement of this technology, such as spreading factor, bandwidth, transmission power, coding rate, and carrier frequency. The third section delves into the LoRaWAN protocol, which functions as the MAC layer for LoRa. This section provides a detailed analysis of the operational modes of LoRaWAN, as well as the connection methodologies employed between end devices, gateways, and network servers, including adaptive data rate, slotted ALOHA, and TDMA, .etc. Finally, the next chapter 3 will present the relevant studies and assesses the whcih performance metrics have been studied, ultimately concluding by evaluating their contributions to the field.

Chapter 3

Literature Review

3.1 Introduction

This chapter reviews proposed methodologies and prior research related to this subject from multiple perspectives, including literature, historical context, and strategic implications. The main subjects are the adaptive data rate and time slot techniques used. It analyses the most significant studies for ADR with both scenarios, single gateway and multi-gateway, according to their performance metrics such as packet delivery ratio, energy consumption and throughput. In addition, this chapter analyses TDMA protocols based on LoRaWAN as well. Particularly, the design of the Time Slot Protocol (TSP)in LoRaWAN provides detailed information about the construction of time slot frames, guard time, drift time, and the limitations encountered during the design process. The chapter includes an in-depth discussion of the top implemented ADR schemes and time slot protocols, along with a comprehensive comparison and evaluation. Additionally, it addresses challenges and design considerations using various aspects such as multi-gateway support, roaming capabilities, system capacity, propagation time, battery life, and security. Finally, the chapter is summarised.

3.2 Systematic Research Methodology

In recent years, numerous MAC methods and protocols have been proposed. These protocols can be broken down into two distinct categories, namely, those that are contention-based [73] and those that are schedule-based [3]. Contention-based media access control protocols are primarily random access protocols, including Slotted-ALOHA and Carrier Sense Multiple Access (CSMA), in which all nodes keep listening to the shared medium and compete for it in order to transmit data. Multiple nodes gain access to a collision-free medium that is partitioned according to time (TDMA) or frequency in the schedule-based protocols. This medium is predetermined (FDMA). Second, Slotted-ALOHA is an offshoot of ALOHA that relies on the relative synchronisation of nodes to bring about interference reduction and peak channel capacity. Time is typically divided into a number of identical time slices, with all nodes gaining access to the channel simultaneously at the start of each slice. If a conflict arises, the transmission must be delayed until the start of the next slice.

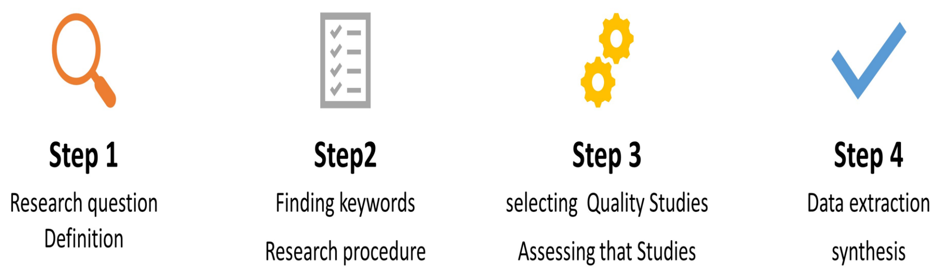


Figure 3.1: Process of systematic review

The chapter's goal is to draw attention to these specific aspects of LoRa technology that must be considered in the adaptive data rate configuration and the design of a Time Slot Frame (TSF) to report on the state of current TSP implementations and to offer some insights into the associated challenges and opportunities. To our knowledge, this is the first study devoted to a Time Slot Frame in LoRaWAN Protocol and gives a wealth of information concerning spreading factor allocation. The contributions in this chapter are summarised below:

- Review of the leading adaptive data rate schemes, particularly LoRaWAN-based spreading factor allocation that have been published so far, including joining techniques, configuration algorithm.

- Review of the leading Time Division Multiple Access (TDMA) schemes, particularly LoRaWAN-based time slot frames that have been published so far, including joining techniques, scheduling algorithms, synchronisations, and the Acknowledgement slot.

- Comprehensive comparison of Time Slot protocols considering their performance in terms of time slot frame information design, including acknowledgements, scalability level, propagation latency and how these protocols handle roaming and encryption.

- Summary of the challenges and considerations that should be taken into account when designing a time slot frame.

- Identification of the research gaps of interest to researchers and providing a summary of the leading Adaptive Data Rate schemes that have been published so far.

In this section, the approach adopted to obtain a systematic research review connected to the current PRISMA Criteria steps will be described based on Figure

3.1, 3.2. On the basis of the findings of the SR, in to bath ADR and TDMA methods based .The SR places an emphasis on some of the defined research questions, which helps to differentiate between and analyse the research data that are relevant to the questions. The analysis is broken down into various steps, the first of which is the collecting of resources in the form of standardised journals to enable a literature review, followed by an assessment of the leading research studies on ADR and TDMA.

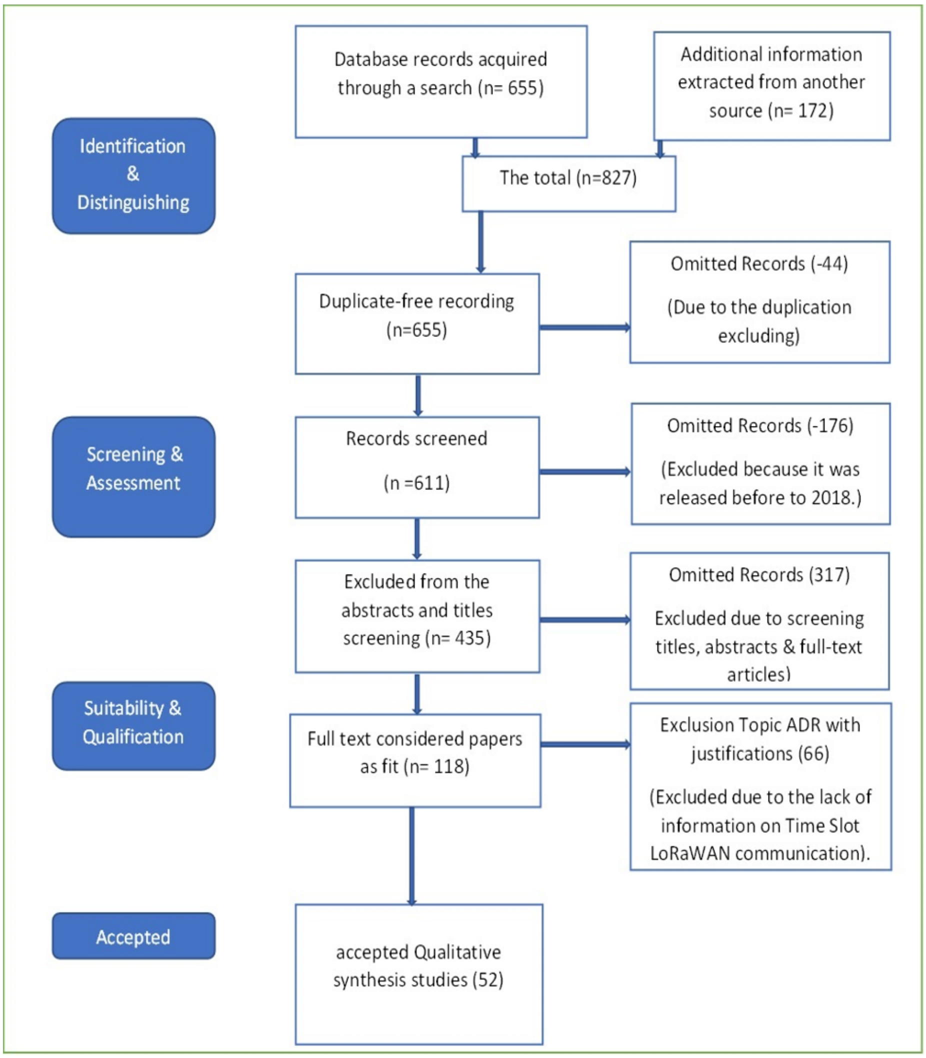


Figure 3.2: PRISMA full systematic review procedure

3.2.1 Searching Keyword and Procedure

The process of locating and searching for keywords includes both the filtering of the results of the search and the creation of a time limit for the investigation. Through a prototype search that covers only the years 2018 to 2025, the search is confined to electronic databases. When executing a search, Boolean operators are used, and each database provides a unique set of search options. The majority of databases use a standard search string, while the others have slight variances. The internet search relied on IEEE Explore, Scopus, Google Scholar, Elsevier, MDPI, and Wiley online library to scour the electronic versions of the systematic reviews. These online resources were chosen to serve as primary sources not only due to the fact that they hold a significant number of archival records of the research conducted on LoRaWAN, but also due to the fact that it was determined that these databases are the most appropriate ones to use in order to obtain comprehensive published research regarding the research questions that were chosen for this Systematic review.

Table 3.1: Inclusion and Exclusion Criteria for the Systematic review.

Research availability	Full text	Articles without full-text access are omitted.
Language	English	studies and articles written in languages other than English are not considered.
The historical	From 2018 to 2025	Papers published before 2018 or lacking essential bibliographic details such publication date, journal type, issue number, and volume number were not included.
Investigation question	At least one research issue must be addressed in these papers.	Paperwork that has been duplicated (the most recent paper containing the necessary information is included, while the others are omitted).
Which layer studied	Datalink Layer (LoRaWAN) specifically (Time Slot Technique)	Physical Layer studies

3.2.2 Assessing and Selecting leading Research

In order to choose and assess the quality of published research, inclusion and exclusion criteria are applied after the keyword and search strategy have been established. This criterion aids in selecting studies pertinent to the current investigation. This approach excludes review articles and book series, whilst including only the highest-quality journal papers from reputable sources that objectively explore the consequences of this technology. In addition, publications from 2018 to 2024 have been selected, as this is the optimal timeframe for demonstrating the advancement of research. Additionally, only studies that only concentrate on LoRaWAN communication are included in the research; all others are removed. The criteria for acceptance and rejection in the current review process are shown in Table 3.1.

3.3 Leading Published Research in terms of Adaptive Data Rate (ADR) Algorithms

As of October 2024, the IEEE Xplore database includes 4,240 publications with the terms 'LoRa' or 'LoRaWAN' in their titles. This section provides an overview of high-impact research papers, beginning with applications of LoRaWAN to justify the thesis emphasis on LoRa. It then addresses the MAC layer aspects of LoRaWAN, particularly LoRaWAN scalability, energy consumption, and examines network lifespen, which are pertinent to the focus of this thesis.

In this section, recent published research provides evidence regarding issues relevant to LoRa networking with useful solutions. The scope of this chapter focuses on LoRa as a physical layer, and LoRaWAN as the communication protocol of LoRa, particularly in terms of the ADR based on SF allocation and Time Slot approachs which relies on the TDMA Communication Protocol. This article has set up further research questions based on an article of the current literature and a search for a gap in the literature. Here's what they are:

- What are the most significant studies in Adaptive data rate?
- What are the components of the TSF structure and what are the limitations of the TSF design for LoRaWAN?
- What are the most effective LoRaWAN techniques shown to date?
- Are there any challenges or factors that must be taken into account when designing the TSF? In-depth analyses of how these factors affect the TSF of the LoRaWAN network have led to solutions for some of these problems as a results of these questions.

3.3.1 Adaptive Data Rate

The Adaptive Data Rate (ADR) is a functionality present in the LoRaWAN protocol that allows for the automatic modification of transmission parameters specific to each end device, taking into account the current network conditions. The primary objective of ADR is to maximise network efficiency, improve capacity, and extend the battery life of devices. ADR functions at the network server level and utilises diverse parameters to ascertain the most favourable transmission configurations for individual devices. The metrics encompass many signal quality measures, including received signal intensity, signal-to-noise ratio, and levels of network congestion. ADR can change the essential transmission parameters, including the SF, CR, and transmit power. The Spreading Factor is a crucial parameter that influences the bandwidth of the signal and has a significant impact on both the transmission range and data throughput. Increasing the spreading factor results in an extended coverage area, hence enhancing the range of communication. However, this comes at the cost of reduced data transmission rates. ADR is a mechanism that modifies the spreading factor in response to the prevailing signal conditions, with the aim of achieving an optimal trade-off between the range of communication and the data rate [74]. The objective of the standard ADR algorithms is to minimise the value of SF, hence facilitating connectivity between the ED and the GW, with the aim of minimising energy consumption. The method implemented on the network server is developed by the server developer, whereas the algorithm operating on the end ED is specified by the LoRa Alliance [75]. The NS algorithm commonly refers to the implementation utilised by prominent platforms such as The Things Network or The Stack Things. This implementation is founded on Semtech's suggested method [76]. ADR in LoRaWAN facilitates the adaptive modification of transmission parameters between a node and the network server. When a node tries to become part of the network, it utilises the device's default transmission parameters for connectivity and sets the ADR counter to zero. The counter is incremented with each subsequent transmission, and it resets to 0 upon the reception of an ACK. Following a series of transmissions that did not receive a response more than (ADR_ACK _LIMIT) the value of TP is augmented. When the node achieves its maximum TP, it subsequently increases the SF to get connected with NS.

The aforementioned procedure is iterated for each ADR_ACK_DELAY transmission until either a response is successfully received or the node achieves the maximum values of spreading factor f and transmit power TP. The customizable settings of ADR_ACK _LIMIT and ADR_ACK_DELAY are set to a default value of 32 [77]. The network server assesses the quality of the connection. The evaluation of connection quality by the NS is accomplished by utilising signal-to-noise ratio measurements conducted at the GWs. The method calculates the necessary number of TP or SF adjustment steps to achieve a stable communication state, considering factors such as link quality, sensitivity for each spreading factor and SNR [78], and an error margin (margin_db). In each procedural iteration, the neural system provides instructions to the executive director, specifying whether to decrease the scale factor or patient variable or to increase the patient variable. The channel estimate process takes into account the highest SNR value, denoted as $SNR - m$, obtained from the N most recent transmissions. The value of the variableN_{step} is equal to the number of changes in connection strength. The node modifies its settings in response and carries out further communications. This repeated reconfiguration leads to more consuming power of nodes. Another concern with this strategy is the magnitude of the step in TP level and SF. Some authors have attempted to address this issue by reducing the or increase in TP_{level} by one dBm, as demonstrated by [79][80][81]. However, the step size of SF remains unchanged.

3.3.2 ADR Schemes for Single gateway

ADR is commonly used to describe the process of finding the sweet spot for the SF, TP, CF, and CR values that are assigned to individual LoRa nodes and networks. Different data rates and airtime from varying transmission parameter sets have a noticeable impact on the network's throughput, energy consumption, and fairness between nodes. For example, nodes further from the gateway typically tune a bigger SF to sacrifice throughput for reach, which requires more time and power required for transmission. To optimize the throughput of LoRa networks and reduce their overall energy consumption, it is essential to have a reliable method for setting the network configuration. The existing configuration settings approachs primarily aim to determine the optimal parameter sets for LoRa nodes in light of deployment topology, communication behaviour and channel conditions. There are many performance metrics that have been studied, such as I.throughput and energy consumption fairness and packet deliver ratio taken as optimization targets; II. A system or link model formulated based on the optimization problem. Since the SF, BW, and CR setting defines the data rate of LoRa radio, the ADR technique is also considered a configuration setting as well.

The most related studies to adaptive data rate are surmised in Table 3.2, and Table 3.3 Clearly indicate which performance metrics have already been studied and which ones have not. The SF assignment enables LoRa to regulate its transmission sensitivity through an ADR scheme, which concurrently manages additional physical layer parameters, including the transmission power of the end device and the coding rate[82]. A high SF is associated with a lower rate of chirps transmitted per second, resulting in a reduced amount of data encoded per second. A high SF enables LoRa-enabled end devices (EDs) to achieve long-distance transmission; however, this results in an increased probability of collisions due to the low data rate. A relay control scheme was proposed for a scalable and equitable LoRa network in [83]. Fairness involves equalising the success probability across each SF region, while scalability is facilitated by multiple relay nodes utilising a similar SF to mitigate interference in dense star topology-based networks, where EDs communicate directly with GWs to transmit source data via the LoRa communication channel. This work presents an analytical model for success probability in managing relay operations, taking into account various independent factors related to the signal-to-interference ratio (SIR) and signal-to-noise ratio. Additionally, the coverage probability across the entire network and the minimum success probability for each SF region were optimised to guarantee fairness. The RSSI values informed the relay selection mechanism, determining whether to forward the received packet from the source ED. The enhancement of LoRa performance was the focus of studies [84] and [85], which proposed an efficient SF allocation scheme informed by RSSI values and SIR. A heuristic method for SF allocations was developed in [84] to demonstrate the necessity of assigning larger-than-required SFs. Sequential waterfilling was employed to develop an advanced SF assignment scheme [85], representing an improvement over the prior work [84] by the same authors. Fairness was achieved by standardising the time-on-air for transmitted packets utilising various SFs. Furthermore, SFs across various GWs were equilibrated with respect to the channel capture effect. Stochastic geometry informed the development of a heuristic SF allocation algorithm [86], wherein the packet success probability expression was derived for co-SF interference scenarios in relation to SNR values. With LoRa, customers have access to six SFs for data transmission, but there is a temporal limit on the number of virtual channels that may be used.

In order to ensure that a maximum number of devices may transmit successfully, the network capacity is defined by the restricted number of virtual channels, which in turn limits the number of simultaneous uplink TX to the GWs. When the network's capacity is exceeded, packet collisions happen, leading to a significant drop in network performance. To simulate the compromise between virtual channel allocation and network capacity, game theory was suggested[87]. The goal was to minimise ED wait times by limiting the usage of each SF to a certain timeframe. According to [88], the user requirements for LoRa were taken into account, and in order to minimise collisions and meet the limits of duty-cycle co-SF interference, numerous channels were planned. To avoid packet collisions and increase communication range, the authors assumed perfect SF orthogonality and used efficient joint channels and SF allocation. Asynchronous random-access protocols are used by the LPWAN, for example, the MAC layer's pure Aloha protocol. The high packet collision probability of these protocols is a result of the fact that several nodes may use the same frequency channel to transmit their acquired data at the same time. To address the packet collision problem, the authors proposed carrier sensing and centralised resource management. Although carrier sensing is not viable for LoRa networks due to their huge coverage areas, centralised systems are not suited for LoRa networks due to their high energy consumption. In order to automatically control the TX time and prevent duplicate packet TX, the authors of[89] proposed using machine learning. These are some of the studies of ADR in a single gateway, while ADR with multi gateway is discussed in the next section.

3.3.3 ADR for Multi-Gateways Schemes

Due to the rising interest in IoT devices, particularly in the vibrant and busy urban environment of the downtown region of the city, GW densification emerges as an efficient approach to deal with the increased density of IoT electronic devices in the target area. As a result, LoRaWAN networks have resorted to dense GW deployment, which should be carried out while avoiding the significant interference that occurs between the huge IoT ED and densely placed GWs. Due to the fact that the current densification procedures that have been recommended for cellular networks are not suited for the LoRaWAN use case, new densification strategies need to be developed. This pertains to the sophisticated coordination that occurs both inside and between cells in order to manage the radio resources, which is not the case with LoRaWAN [9]. Analysing multi-cell LoRa networks to scale them was proposed as a GW densification strategy in [90]. Free co-SF interference in dense networks was achieved by deploying several GWs. The suggested model takes into account the interplay between GWs and a few unique LoRa technology characteristics.

By using methods such as homogeneous Poisson point processes to randomly distribute GWs and EDs over the target region, mathematical analyses were conducted to determine the scalability and coverage of the deployed LoRa GWs. We found that GW densification improved the network's coverage and scalability. Thus, the author used coverage probability using stochastic geometry tools [91] to measure the network's performance. Under various fading models, the coverage probability of edge EDs with a randomly dispersed node was thoroughly investigated in [92]. Taking into account interference from the LoRa network itself, known as co-SF interference, the coverage of LoRa connections was investigated in [93] when several GWs were present. The likelihood of ED coverage under these interferences was represented using a stable distribution and was derived from stochastic geometry, which views interference from underlying technologies (such cellular communications) as impulsive noise [94].

According to the research, the likelihood of coverage for the LoRa network is much diminished when underlying technology is present in the area, and this effect becomes even more pronounced when the deployment of pace GWs is taken into account. In order to handle the advantage of installing many GWs and leveraging FEC to improve the load resilience of the LoRaWAN network, an ADR mechanism was proposed in [95]. An important factor in determining the sweet spot for LoRaWAN network performance is the frame error correction, which is the physical loss between an edge device and a single gateway independent of frame repetition. Modifying the ED's TX settings as it communicates via a channel modelled from experimental measurements over a public LoRaWAN network with many GWs and FEC is the essence of the suggested technique. For the purpose of assessing the improved ADR scheme's efficacy, the data loss ratio — represented by the data error rate — among the EDs and the application server was extrapolated from the suggested channel model. To facilitate firmware upgrades in dense LoRaWAN networks, network densification was proposed in [96]. It is necessary to upgrade the ED firmware to enhance its functionality and additional security measures, knowing that the firmware update is important for EDs to fulfil their responsibilities properly. Due to the large number of EDs in outlying locations that need software updates on a regular basis, updating the firmware is a difficult process, even if it extended the network's lifetime and increased its performance. Firmware update over the air (FUOTA) is a novel approach that was developed in [97] to address this issue. It enables the remote execution of firmware upgrades using a wireless medium. For LoRa to be deployed in massive IoT, it is crucial to plan and determine the optimal location of the minimum number of GWs to increase the number of EDs covered by the network. As GWs define LoRa performance, the authors of [98] developed a GW planning scheme for hybrid LoRa networks.

3.4 Leading Published Research in terms of TDMA Schemes

TDMA protocols allow several nodes to communicate on the same frequency in distinct time slots, sharing the same transmission channel without collisions. However, there is no synchronisation technique [99]. An approach called on-demand Time Division Multiple Access (TDMA) that uses low-energy wake-up radios and supports both unicast and broadcast modes for triggering nodes and allocating time slots, respectively, was proposed by Piyare et al. [65] . Gu et al.[100] devised a TDMA-based LoRa multi-channel transmission control with an urgent ALOHA channel and negative acknowledgement (ACK) for wireless sensor networks' one-hop out-of-band control layer. The most important issue for TDMA MAC research is time slot scheduling and allocation. To schedule transmissions, Haxhibeqiri et al. [66] depend heavily on network synchronisation and scheduling entity (NSSE) as the LoRaWAN network's core scheduler.

In particular, the node transmits a request including the traffic periodicity to the NSSE and receives a response regarding the assigned time slots encoded in a probabilistic space-deficient data frame structure. However, given a certain chance, many nodes may occupy the same slot, resulting in collisions. Abdelfadeel et al. [3] presented the FREE system for fine-grained scheduling. Nodes are specifically allocated transmission parameters including SF, TP, and time slot, and then execute bulk data transfer in the preset time slot. However, while FREE eliminates the collision issue, it does not support real-time transmission. In order to facilitate real-time low transmission, Leonardi et al. [67] suggested RT-LoRa, a revolutionary LoRa MAC protocol that can replace LoRaWAN. When using RT-LoRa, the duration of a time slot is constrained by the smallest possible packet size and changes among SFs 7, 8 and 9 due to their high data rate as illustrated in time of symbol Figure 2.2. Zorbas et al.[23] presented TS-LoRa, an auto time-slotted communication system based on creating hash functions mapping the nodes' provided addresses into unique slot numbers, so as to eliminate the need for the centralised scheduler to supply unique time slots for all nodes. In addition, floating nodes suffer greater losses in signal strength and packet errors as a result of their dynamic attitude as compared to those mounted statically on the ground. This is because the polarisation and directivity of the antenna are affected by the orientation of the antenna. Consequently, Wang et al. [68] suggested a channel access approach called PolarTracker, which makes use of the node's attitude alignment status to plan broadcasts during best-aligned times for higher connection quality.

3.4.1 Time Slot Structure

The frame's structure comprises several uplink slots, guard times, and downlink slots based on the different schemes. The repetition of the frames over the course of time serves as a method of synchronisation as well as acknowledgement.

- **Time Slot Frame Size**

  In a time-slotted setting, events occur in discrete slots rather than continuously. Since only one node at a time may claim a given 'slot' it stands to reason that the total number of slots available in each frame must be exactly equal to the number of nodes. On the other hand, owing to limitations imposed by the duty cycle, this is not always possible. If the duty cycle is 1%, then the amount of time that must pass before a node may broadcast again is equal to 99 times the length of its most recent transmission. Therefore, the interval between two consecutive transmissions must be filled with either another transmission (a slot), or with empty slots [101]. This requires a minimum frame length when the number of transmissions is insufficient. TS-LoR [23] and FREE [3] assumed that each frame has one downlink slot and two Guard Times(GT), so the frame size was calculated as follows:

- **Guard Time**

  The guard time is the amount of time that elapses between the ending of one slot and the start of the following one. Choosing appropriate values is necessary since the timing precision of the synchronisation approach and the inaccuracy of the transmission start timings of end devices both play a role in the decision-making process. The clock drift of the nodes necessitates guard times between slots as with any conventional time-division protocol. It's possible that LoRaWAN's guard times will need to be greater than in other IoT protocols because of the longer guard durations and, by extension, the longer timeslots and frames. In addition to this, system designers must think about the varying slot lengths of each SF, the number of nodes in each frame, and the frequency of synchronisation. To accommodate the longer time periods of transmissions at higher SFs, guard times must be shifted upwards. Furthermore, if the synchronisation periodicity occurs every few frames rather than at each frame, then the guard times could be significantly longer.

- **Drift Time**

  Inaccurate sensor clock timing is the primary cause of delayed transmission starts. Low-cost devices are prone to such issues because of the inherent instability of oscillator crystals. The oscillators provide a timing uncertainty because they might operate either too slowly or too quickly. The fractional part-per-million difference from the nominal frequency is one measure of this uncertainty (ppm). Time uncertainty of 200 ms occurs at intervals of 2.64 hours, 53 minutes, and 40 minutes for common deviations of 20 ppm, 60 ppm, and 80 ppm, respectively [55]. Periodic synchronisation is necessary to avoid these time drifts from becoming unmanageable. A maximum for the expected time drift can be calculated from the clock synchronisation frequency if the tolerances for the crystals used in the final devices are known. Using this number, a safe amount of time for a guard to stand watch can be estimated. This study supposes that all clocks induce negative drift, meaning that all of them operate at a rate lower than their stated frequency. A similar climate makes this a reasonable assumption [102].

3.4.2 Time Slot Frame Limitation

According to several studies on time slotted frame, still there are many obstacles to making it more flexible in order to enhance scalability on LoRaWAN, including the following important limitations.

- **Duty Cycle Regulation**

  The constraint on the duty cycle is the source of many problems that arise within a LoRaWAN network, including the restricted availability of gateways, transmission delays, and lengthy registration periods[49]. For the most part, LoRa uses ISM bands below 1GHz, where radio duty cycle and transmission power limitations are enforced by local authorities. ISM band 868, which spans from 863 to 870 MHz, is used by LoRa devices in Europe [103]. According to Table 3.4, the majority of these sub-bands have a maximum allowable Equivalent Isotropically Radiated Power (EIRP) of 25 mW (14 dBm) and a radio duty cycle restriction of 1%. As a result, the hourly uplink time is reduced to 36 seconds. When this time is split up into many transmissions, there must be a period of inactivity equal to 99 times the length of the time it took to send the previous transmission.

  However, with LoRaWAN, the second receive window has its dedicated channel with a 10% higher duty cycle. Otherwise, all other gateway duty cycle requirements apply Table 3.4 [104]. The periodicity of the data created in the application must always be kept in mind before beginning work on the design of a time-slotted system. If a certain application needs a new packet every 30 seconds, for example, then the maximum frame length must be kept within that threshold. This is a concern for network capacity since it reduces the total number of slots that may be reserved in a single frame. Increasing the SF and the number of slots causes a dramatic growth in the frame size. Therefore, it is important to maximise frame size, as it allows for a higher maximum duty cycle to satisfy application needs. Thus, not all SFs may support all applications, and certain applications may only work with frames that have a very small number of nodes. The efficiency of parallel transmission would be using the fastest data rate to predict all SF's connectivity.

- **Acknowledgement Frame and Downlink**

  Downlink transmissions are particularly problematic due to the radio duty cycle limitation. It seems that when uplink traffic is heavy, gateways may be unable to individually acknowledge all the transmissions or send out command packets, leading to a large number of retransmissions and a corresponding rise in power consumption. Due to the half-duplex nature of LoRa transceivers, a gateway never accepts data while being utilised for downlink broadcasts, further compounding the situation. In a time-slotted system, an acknowledgment may be delivered simultaneously with the data transmission slot, or in a separate time slot at a later time. In the first situation, it is challenging to manage the available downlink time resources due to the fact that a receiver might receive several packets in a short period of time. This makes it difficult to manage the available downlink time resources[102]. The second scenario provides more leeway for customization, but at the cost of added time. Aside from that, additional overhead is needed for every downlink contact, which is why downlink broadcasts have to be as condensed as they can possibly be.

- **Unequal Frame Length**

  In contrast to conventional radio technologies, increasing the SF results in a longer LoRa transmission times (for the same payload). This implies that unless all the nodes use the same SF, the slot length will always differ for each transmission. Time slots of similar duration (for example, based on SF12) are inefficient because they cause transmission delays and have a low capacity. Having many frames, each of which is committed to a different SF, might help with this issue. Parallel processing of LoRa frames is possible since the SFs are almost orthogonal to one another. Collisions caused by inter-SF interference can be remedied by increasing or decreasing the nodes' transmission powers [3, 105], or by designating a unique channel for each frame (SF) [101]. Both options, however, may require some fine-tuning of the nodes.

3.5 Implemented Time Slot Protocol

The current state of TSP systems, including both working and experimental implementations, as well as their strengths and limitations, are discussed here. Moreover, ideas to address some of the unresolved problems related to TSP and how these solutions deal with, or at least lessen, the impact of some of the difficulties mentioned earlier will be developed within this section. It is important to highlight that certain TSP techniques have been proposed in the literature [3, 23, 24, 106, 107, 108, 109] without having been subjected to experimental testing or validation.

3.5.1 TS-LoRa

As an alternative to LoRaWAN, TS-LoRa [23] has been proposed for use in situations where frequent and highly dependable transmissions are necessary. Nodes are able to independently organise their time slot schedules within frames due to TS-LoRa. In order to accomplish this goal, the network server and the nodes share a hashing method that is simple to compute. This technique converts the addresses of the nodes, which are given out during the join phase, into integers that are exclusive to each slot. Backward compatibility with legacy LoRaWAN nodes is ensured by the technique, and TS-LoRa is freed from the burdensome overhead of schedule distribution. The frame length is the only piece of information that the network server must deliver while using TS-LoRa.

The network server sends out a broadcast message to all of the nodes at the same time since this piece of information is the same for all of the nodes.
TS-LoRa is scalable due to this, in contrast to previous time-slotted techniques for LoRaWAN that have been presented in the literature. In addition, the final slot of each frame in a TS-LoRa transmission is reserved for the transmission of the 'SACK' packet, which is responsible for time synchronisation and acknowledgement slot. To confirm receptions from all available slots simultaneously, the network server combines several acknowledgements into a single packet. The TS-LoRa protocol was subjected to experimental testing, and the findings showed a very high packet delivery ratio for all of the different spreading variables that were examined. As is the case with all applications that could be verified, acknowledgements incur additional costs in terms of energy. Alternatively, as shown by the simulation results, these costs are much lower than that of LoRaWAN when confirmable traffic is supported. TS-LoRa [23], the passage of time is broken up into a series of repeated frames, and each frame is made up of a number of timeslots. In most cases, the size of a time slot is predetermined and is dependent on the chosen payload size, as well as the characteristics of the radio. Multiple users are able to share the same radio frequency in this manner without the risk of causing interference to one another by being assigned to different time slots. The allocation of time slots is an essential step in the execution of every time-division protocol, and it is typically the responsibility of a centralised coordinator (e.g., in cellular networks). Finally, in spite of the fact that TDMA communications have been studied for decades and are relied upon by many real-world applications, the design of new Time-Slotted LoRa is an extremely challenging problem due to the unique characteristics of LoRa radios and the duty cycle restrictions in sub-GHz ISM bands.

3.5.2 FCA-LoRa

In Fair Collision Avoidance (FCA-LoRa), scheduling is handled via gateways [108]. In a process known as the Gateway Duty Cycle (GWDC), every gateway periodically swaps off its transmission channel while broadcasting beacon frames.

The gateways in each GWDC have sent their beacons across all of the channels that are accessible to them. This synchronises the LoRa nodes and makes it possible for any node that is put in the appropriate distance to receive them regardless of the channel that they listen to. By employing the same channel via which the most recent beacon was received, nodes are able to effectively deliver their data to a gateway since they have taken use of the scheduling information that beacons provide. To further improve reception likelihood and favour channel use, each LoRa gateway uses a unique SF value during beacon broadcast. In common with the older LoRaWAN, FCA-LoRa relies on gateways to oversee the incorporation of new LoRa nodes into the network. A join request message is sent by a LoRa node once it has received its first beacon from a gateway. The gateway then relays its reply and the subsequent beacon across the appropriate channel. LoRa endpoints listen for the most recent beacon transmitted by each gateway in order to synchronize their clocks. Beacon frames allow LoRa nodes to select from a variety of SF values for each transmission, hence increasing the likelihood of successful reception at the destination gateway receiver. In addition, FCA-LoRa promotes the adoption of a scheduling method known as duty-cycle-aware scheduling, which requires LoRa nodes to take into consideration duty-cycle constraints in order to make the most efficient use of each channel.

The goal of the FCA-LoRa project is to assure justice and improve LoRaWAN performance by using an organized bandwidth allocation strategy which takes advantage of the scalability of the network and eliminates LoRa gateway receiver conflicts. The FCA-LoRa protocol developed in OMNET++ by Framework for LoRa (FLoRa) is a discrete event simulator[110]. FCA-LoRa improves the performance of the conventional LoRaWAN scheduling strategy in terms of throughput and collision avoidance, as demonstrated by their simulations in OMNeT++.

3.5.3 SBTS-LoRa

The network field is divided up into annulus cells using the SBTS-LoRa protocol[109]. Every cell has its unique frequency, a different list of qualified

SFs, and a different degree of transmission power. Nodes that are positioned on the edge of a particular cell will make use of the transmission characteristics that have been designated for that cell. Similarly, SBTS-LoRa works by dividing each cell into a few different sectors. The sector ID that a node is a part of determines whether or not it is allowed to transmit during a certain timeslot ID. SBTS-LoRa's enhancement utilises a decentralised mechanism for choosing node transmission parameters. This allows the network to avoid becoming stalled by an excessive amount of control packets coming from the network server. Therefore, nodes autonomously decide their transmission parameters and timeslot based solely on the gateway's location and identification. SBTS-LoRa does not require beacons from the gateway to control nodes. SBTS-LoRa employs TDMA for uplink transmissions without breaking the LoRaWAN specification. Therefore, SBTS-LoRa might be simply integrated into LoRa networks with few changes. In SBTS-LoRa, the nodes decide autonomously when to send and receive data without relying on downlink transmissions from the gateway. To be more precise, each node chooses its slot number and, consequently, its transmission time based on its distance from the gateway. SBTS-LoRa has a set cell frame size. The slot duration varies based on the SF and cell's frame size relies on the end-node angle, which depends on the cell radius. The proposed protocol is developed primarily at the application layer of nodes in the FLoRa architecture [80]. The SBTS-LoRa protocol is totally distributed, necessitating no modifications to the network server entity of the FLoRa architecture. The simulation findings demonstrate significant improvements in network speed, collision rate, and energy usage. Specifically, the average throughput of SBTS-LoRa is approximately 13 times more than that of ADR-LoRaWAN in large-scale dense networks.

Table 3.2: Summry of most significant previous studies

N	Metthod ref	Methodbased	Methodology	Collisions	Scala-bility	Energy Efficiancy	Throu-ghput
1	Ihirri et al.		Slotted-ALOHA with synchronization leveraging FM-RDS broadcasting	Low	×	×	✓
2	D.-Y. Kim et al. (2017)	Machin Learning	Logistic Regression	High	✓	×	×
3	Hauser and Hegr (2017)	Machin Learning	Variable Hysteresis	High	✓	×	×
4	Mariusz Slabicki (2018)	n/a	n/a	High	✓	×	×
5	B. Reynders et al. (2018)	Coarse-grained Scheduling	Light-weight scheduling	High	✓	×	×
6	Lim and Han (2018)	Mathematical Optimization	CSMA algorithm	Medium	✓	×	×
7	K. Q. Abdelfadeel et al. (2018)	Adaptive data rat	n/a	Medium	×	×	✓
8	Harwahyu et al. (2018)	Machine Learning	n/a	Medium	×	✓	×
9	Dawaliby et al. (2019b)	Machine Learning	Maximum Likelihood Estimation	Medium	×	×	✓
10	Khaled Q. Abdelfadeel1 (2019)	TDMA	Scheduling and synchronization	Very Low	✓	✓	×
11	Amichi et al. (2020)	Mathematical Optimization	Bulck Data method	Low	×	×	✓
12	Premsankar et al. (2020)	n/a	Linea & Quadratic Approximation	Medium	×	✓	×
13	Sallum et al. (2020)	Mathematical Optimization	Mixed Integer integer Linear Programming Distributed	Low	×	✓	×
14	Narieda et al. (2020)	Constrained Optimization	Genetic Algorithm	Low	×	✓	×

Table 3.3: Summry of most significant previous studies - Continued

N	Metthod ref	Methodbased	Methodology	Collisions	Scala-bility	Energy Efficiancy	Throu-ghput
15	J. Finnegan et al. (2020)	ADR NS-side And ED-side	n/a	Low	✓	×	×
16	Kang Yang, et al. (2024)	Experiment	cross-interface downlink relay	Medium	✓	×	✓
17	Wang, Ruiqi et.al.(2025)	Reinforcement learning	n/a	Very Low	✓	✓	✓
18	(Pham & Ehsan, 2021)	channel access mechanism	CSMA algorithm	Low	✓	×	×
19	Mahmood, Aamir et.al.(2019)	interference cancellation	Stochastic geometry	Medium	✓	×	×
20	ounsi, Hajer et.al.(2024)	TDMA	Optimisation	Low	✓	×	×
21	(Park, Lee, & Inwhee, 2020)	Resource optimization	Deep learning technology	Low	×	✓	×
22	(Al-Gumaei, Y. A. and Aslam, N. 2022)	Resource optimization	Power Allocation	Low	×	✓	×
23	(Loubany, Ali and Lahoud, 2023)	Resource optimization	Adaptive data rate	Low	✓	✓	✓
24	(Park, Lee, & Inwhee, 2020)	Resource optimization	Deep learning technology	Low	×	✓	×

Table 3.4: The EU868 bands and sub-band, TP and duty cycle

Frequency (MHz)	Duty Cycle	Uplink/ Downlink	Downlink stage	Transmission Power mW ERP
863– 865	0.1% or LBT	U/D	RX1	25
865 – 868	1% or LBT	U/D	RX1	25
868 – 868.6	1% or LBT	U/D	RX1	25
868.7 – 869.2	0.1% or LBT	U/D	RX1	25
869.4 – 869.65	10% or LBT	D	RX2	500
869.7 – 870	No requirement	U/D	RX1	5
869.7 – 870	1% or LBT	U/D	RX1	25

Table 3.5: Time Slot LoRa Schemes characteristics.

Property	SBTS-LoRa	FREE-LoRa	TSCH-LoRa	FCA-LoRa	TS-LoRa	Multi-Hop LoRa	Synchronous LoRa Mesh	TS-VP-LoRa
Topology	Star	Star	Mesh	Star	Star	Tree	Mesh	Star
Downlink	X	✓	✓	X	✓	X	✓	✓
Scalability	H	H	M	L	H	M	H	H
Addressing	LoRaWAN	LoRaWAN	IPv6	LoRaWAN	LoRaWAN	Fixed	Fixed	LoRaWAN
Routing	N/A	N/A	RPL, Static	N/A	N/A	Custom	Flooding	N/A
Multiple Gateways	X	X	✓	✓	X	✓	✓	X
Free-Collision	X	✓	Depends on Schedule	✓	✓	✓	✓	✓
Protocol Overhead	L	M→H	V.H	M→H	M→H	H	H	M→H
Timeslot Size	Constant per SF	Constant per SF	Fixed	Fix	Constant per SF	Fixed	Fixed	Constant per SF
Security	LoRaWAN	LoRaWAN	802.15.4, TinyDTLS	LoRaWAN	LoRaWAN	X	X	LoRaWAN
Support IIoT	X	X	N/A	X	✓	N/A	✓	✓
Country of Study	UK	Irland	Denmark	Greece	Irland	Korea	Switzerland	Irland
Implementation Experiments	Simulation	Simulation	Testbed	Simulation	Simulation + Testbed	Prototype	Simulation + Testbed	Simulation + Testbed
Simulator	OMENET++	LoRaSIM	Testbed	OMNET++	LoRaFREE	Testbed	Testbed	OMNET++
Payload Size (bytes)	20	20	100	20	20	60-180	51	variable
Reference	[109]	[3]	[106]	[24]	[23]	[107]	[111]	[108]
Citations	New	72	25	17	103	17	59	New
Publication Year	2021	2019	2018	2021	2020	2020	2019	2021

3.5.4 FREE-LoRa

Fine-grained scheduling for reliable and energy-efficient data collection is defined as a FREE [3]. As a LoRaWAN bulk data collecting protocol, FREE is useful for a broad variety of delay-tolerant uses. Instead of sending data immediately after it's created, the FREE protocol suggests storing it in buffers on the end devices and then sending it all at once during bulk transfers at more practical times. The strength of this approach is in its ability to optimize transmission scheduling, which in turn helps devices operate for longer periods of time without needing to recharge. In addition to increasing the gadget lifetime by a factor of five, bringing it above the ten-year milestone, FREE demonstrated that this method can also achieve a data delivery ratio of greater than 99% (DDR). Scheduled transmissions, which avoid collisions, and the use of larger packets which lower the expense of MAC headers, are responsible for the enhancements. This strategy takes into account an isolated LoRaWAN network, with just one gateway and hundreds of end devices, free from interference from other LoRaWAN networks or other technologies using the same frequency band.

In FREE, the gateway executes the scheduling algorithm based on data gathered from the end devices, such as the quantity of data buffered and the actual path loss. To ensure that all devices' concurrent transmissions are effectively decoded by the gateway, the schedule allocates spreading factors, channels, and transmission powers to devices in order to maximize throughput. The synchronization of FREE comprises two phases: collecting scheduling requests from end devices and supplying them with transmission settings. The second step computes and broadcasts the schedule for all devices using the information collected in the previous stage. During the second phase, the gateway broadcast setting message is encoded with the maximum spreading factor in order to reach all devices. The Frame Settings (Fsettings) message includes the packet length (20 bytes), the guard duration (15 ms), and the number of slots per frame for all spreading factors. Unconfirmed and confirmed communications are simulated using FREE and compared to two other methods. Independent of the transmission method and network size, their findings show that FREE scales well, delivers almost 100% data rate and maintains battery life for over ten years. In contrast, normal LoRaWAN setups have limited scalability, low data delivery, and a device life of fewer than two years in the case of confirmable traffic type.

Table 3.6: Summary of challenges with existing Time Slot LoRa protocols

Issues & Challenges	SBTS-LoRa	FREE-LoRa	TSCH-over-LoRa	FCA-LoRa	TS-LoRa	Multi-Hop LoRa	Synchronous-LoRa	TS-VP-LoRa
Multiple configurations (SF/BW/CR/CF)	6 Sfs/Fixed/ Fixed/3Ch	6 Sfs/Fixed/ Fixed	All Fixed	Random	6 Sfs/ Fixed /Fixed	All Fixed	All fixed	6 Sfs /Fixed/ Fixed
ACK slots	No	Sorted in 1 slot	Sorted in 1 slot	No	Sorted in 1 slot	N/A	1 per slot	Sorted in 1 slot
Joining method	Sector based	Sorted in 1 slot	Beacon-based	Broadcasted Beacons	Aloha + CAD	Beacon based &CAD	Slotted Aloha	Aloha + CAD
Network Size	Fixed per SF& CH	Fixed per SF	Fixed	Fixed	Fixed per SF	Fixed	Fixed	Flexible due to VP
Scheduling-algorithm	Autonomous Base distance	Autonomous	Various options	Broadcasted Beacons	Autonomous	Distributed	On-demand	Autonomous
Synchronisation	No	up to 6 in parallel	During transmissions	During transmissions	up to 6 in parallel	During transmissions	1 dedicated	up to 6 in parallel
Roaming	N/A	In-GT	Re-join	Safeguard	In-GT	Re-join	N/A	In-GT
Encryption (Uplink/Downlink)	Uplink	Uplink only	Uplink & Downlink	Uplink	Uplink only	Unresolved	Optional	Uplink only
Propagation delay	Based p-value	in GT	in GT	With first GT	in GT	N/A	N/A	in GT
Reference	[109]	[3]	[106]	[24]	[23]	[107]	[111]	[108]

3.5.5 TS-VP-LoRa

The aim of the proposed TS-VP-LoRa scheme is to schedule data packet transfers with variable payload from LoRa nodes to the gateways by using specially allotted time slots, thus overcoming the aforementioned difficulties[108]. Based on this new concept, the total available bandwidth is specified by synchronous uplink and downlink channels. Scheduling in TS-VP-LoRa is handled centrally by the network server through the gateways. Using one of the available channels, the gateways regularly broadcast beacons to the LoRa nodes. Multiple concurrent superframes, each corresponding to a different payload range and SF, coexist in TS-VP-LoRa. Frames can coexist in a network depending on the number of channels. In the case of TS-VP-LoRa, the system is made up of simulated superframe structures similar to the structures that are described in [23]. There are a fixed number of time slots forming beacon in [23], and each time slot contains two guard time periods of constant duration to permit minimal delay. The guard time is proportional to the crystal oscillator's drift time and the beacon window's size. In order to determine how many slots can fit into a given superframe, it's essential to determine the time slot size through SF and the payload size. Nodes in TS-VP-LoRa can join the network whenever they choose by sending a join-request message to the gateway (similar to LoRaWAN). After joining, the nodes can tune in to the gateway's broadcast beacons to learn crucial scheduling information. In conventional LoRaWAN, each node chooses a channel at random (among the three required channels) to send the $join - request$ to the gateway, while the SF value is chosen based on the most efficient and reliable value possible given the available resources. The node sending the data packet must determine the payload size, the channel of transmission, and the duty cycle limitations. Before sending a packet, the nodes decide on its size up to 235 bytes (maximum payload at 222 with 13 bytes overhead).

The scheduling scheme's primary goal is to minimise potential collisions between transmissions of varying payload sizes that share the same SFs. To achieve this, researchers have suggested a fair channel scheduling and hopping method which places broadcasts from various payload ranges on separate radio channels. TS-VP-LoRa was created in the discrete event simulator OMNeT++ by making use of the FLoRa (Framework for LoRa) simulation tool [110].

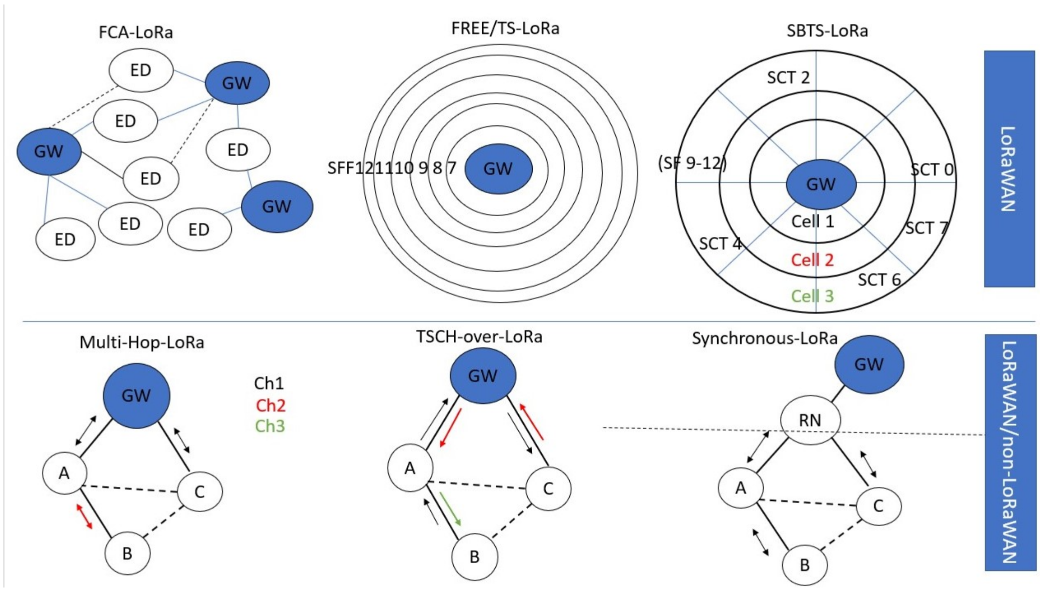


Figure 3.3: The mechanism of each time slot protocol

3.5.6 Comparison and Evaluation

As shown in Table 3.5, some of these protocols have numerous characteristics. However, there are also several notable differences. First, the network design of the majority of Time Slot protocols is a star topology, whereas only TSCH and Multi-hop-LoRa are a mesh topology [107] Regarding addressing, routing, and security, the majority of protocols are based on LoRaWAN addressing, routing, and security, with the exception of TSCH, which uses IPv6, RPL, and static routing correspondingly.

In addition, TSCH is the only protocol that offers compatibility and channel hopping due to its mesh topology, as stated above, but it has the highest overhead compared to other techniques for similar reasons. In addition, each method has a constant and defined time slot size, as well as collision-free operation, which is regarded to be the primary characteristic of TS protocols.

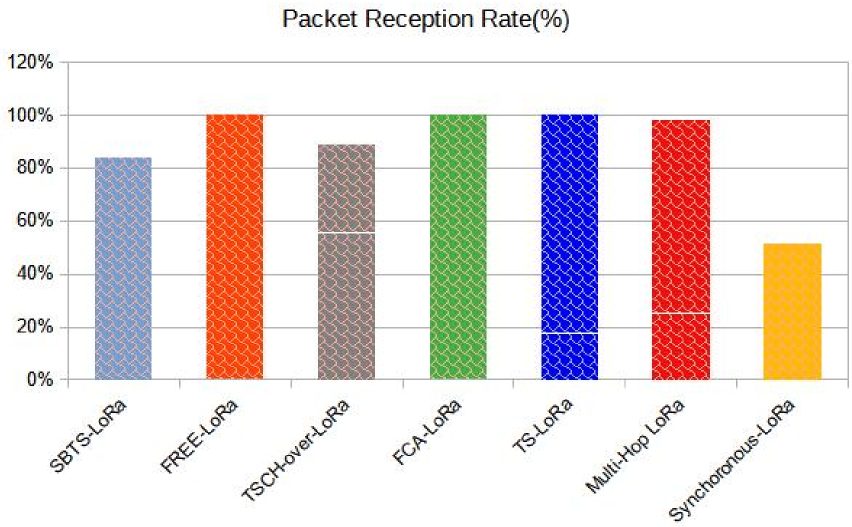


Figure 3.4: Packet Reception Rate of each TSP

As previously mentioned, each protocol has a unique method, which is the second distinction between these approaches.

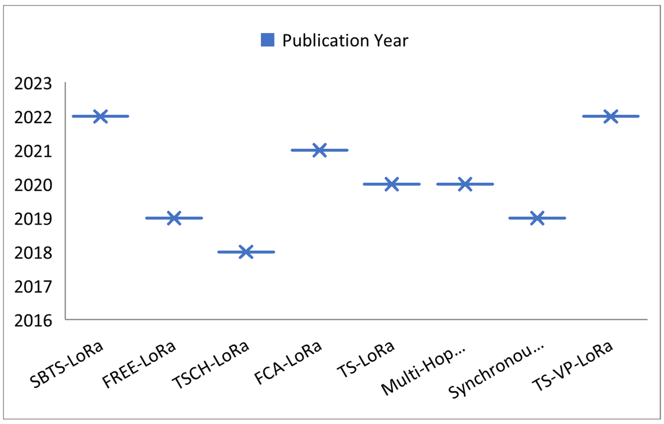


Figure 3.5: Publication Year of each TSP

Several differences, including downlink, scalability, and overhead, are shown in Table 3.5. Some provide acknowledgements, while others do not need acknowledgements, and the methods display varying degrees of scalability and overhead. In addition, certain protocols, such as TSCH, Multi-hope-LoRa, and

FCA-LoRa, employ several time slot frames based on SF, whilst others, such as SF, use only one-time slot frames. The methodologies of those protocols were created by simulation or testbed, with TS-LoRa implemented on the testbed and also simulated. TS-LoRa also supports the industrial internet of things (IIoT). Efforts are focused on the time slot frame in order to increase network scalability and decrease device interference, hence enhancing LoRa as a promising technology. Further challenging factors are shown in Table 3.6 to illustrate how each protocol deals with such issues. The structure and mechanics of FAC-LoRa, FREE, TS-LoRa, and SBTS-LoRa protocols are Pure LoRaWAN and with star topology, whilst Multi-hop-LoRa, TSCH-LoRa, and Synchronous-LoRa are combined with non-LoRaWAN protocols and mesh topology such as those illustrated in Figure 3.3. The second group of those protocols exhaust the available duty cycle resources quickly due to their topology and (often) periodic dense beacon broadcasts. A more in-depth comparison is shown in Table 3.5, represented as TS frame information. The comparison determines how each strategy handles numerous LoRa parameter settings, including SF, BW, CR, and Channel Frequency. Additional information is shown on joining techniques, scheduling algorithms, synchronization, and the acknowledgement slot, in addition to details on propagation latency and how these protocols handle roaming and encryption.

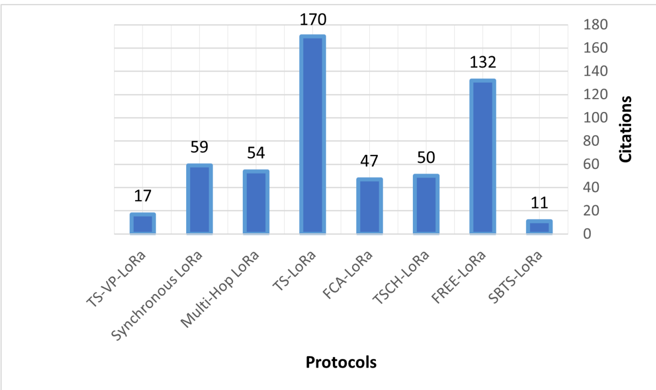


Figure 3.6: The citation of each TSP

The majority of these protocols concentrate on packet reception rate so, the deployment of all of these protocols is either implemented or simulated in a restricted area that is no more than 2 kilometres away. On the other hand, the number of end nodes deployed in these trials has an impact on the PRR; they attempt to improve scalability and prevent collisions. SBTS-LoRA and FREE-LoRa are more scalable than others because their PDR still high with increasing End-nodes of more than 1000 nodes. However, the majority of TSP achieved a high Packet Reception Rate (PRR) with fewer than 1000 nodes as illustrated in Figure 3.4. A large transmission interval might be viewed as mitigating a duty cycle restriction, and the limited number of nodes impacts PRR, so all these factors should be considered in TSP design. Finally, TS-LoRa shows high citation compared to other protocols because it supports IIoT and is simulated and implemented, while other protocols are earlier publications. SBTS-LoRa performs well in the high-density network without an acknowledgement requirement.

3.6 Discussion of Challenges and Considerations for Design

This study analyses the factors to be taken into account and the difficulties to overcome whilst creating LoRa network protocols for time-slotted medium access. In addition this section discussed a number of different time-slotted solutions that have been proposed in the published research available. Particular emphasis has been placed on open-source protocols that have been put into practice and have been subject to experimental testing.

3.6.1 Multi-gateways, Mobility and Roaming

In LoRaWAN, many gateways may receive communication. In such a scenario, a global synchronization mechanism across gateways may be necessary to ensure that these broadcasts do not interfere with nodes registered in a separate gateway. For instance, gates that overlap may share some spaces. Additionally, nodes may move between several gateways. This requires the creation of roaming technologies that allow for seamless movement between various service regions. In such a scenario, the frame size must be dynamically modified to accommodate changes in topology. To expand coverage, it would be interesting to examine how multi-gateway deployments may be implemented in a time-slotted context. If the node moves to a different location, its setting will be reevaluated to obtain a new setting that is suitable for that new location. Thus, a new location means a new setting, a new frame and a new slot.

3.6.2 Capacity

In principle, time-slotted networks are only capable of handling a certain number of connections at any one time. Because of the limits placed on the duty cycle, the data transmission periodicity in LoRa networks may be quite infrequent. This essentially implies that a LoRa-based system would not be able to serve certain applications since they demand frequent packet production. A time-slotted system's frame must have a predetermined maximum number of slots in order to accommodate the periodicity of the data it processes. Because of LoRa's very low data rate, as well as the constraints placed on its duty cycle, the network capacity may be severely limited. However, constructing a time-slotted LoRa system in a way that allows it to support a large number of applications is one of the system's design requirements. Consequently, part of the network capacity needs to be reduced in order to achieve this goal.

3.6.3 Time of Propagation

The LoRa protocol is a type of long-range radio technology that has the potential to achieve a range of several kilometres. Correspondingly, the amount of time required for the signal to propagate might not be considered insignificant. If the design does not take into account this additional time, then there may be issues with desynchronization. This is because signals travel at the speed of light, therefore the propagation time may approach 30 microseconds for nodes that are further apart[112]. Incorporating a maximum propagation time into the guard times is a simple approach that may be taken to resolve this issue. This approach reduces the complexity of the programming tasks, has a delay that is low in comparison to the amount of time it takes for data to be transmitted, does not call for the sending of any additional packets (contrary to cellular networks), and displays negligible delay.

3.6.4 Battery Lifetime

Due to the additional expense of synchronisation, battery life is a critical concern for all time-slotted solutions. This is because receiving the synchronisation message requires the node to have its radio turned on at regular intervals. The evident correlation between packet length and energy efficiency is broken. It is preferable, therefore, to provide as little data as possible so that the fewest feasible bytes are actually transferred. In LoRaWAN Class B, for instance, clients may employ the beacon periodicity to synchronise their timekeeping rather than relying on timestamps sent by the network [105]. For acknowledgements, the data must be encoded effectively to allow for a low decoding computation cost coupled with short payloads if several acknowledgements are merged into a single packet, as previously described. However, modelling studies have shown that the energy cost of re-transmissions in an Aloha-based system may be larger than the synchronisation cost in high-traffic circumstances[23]. Due to (i) the duty cycle limits and (ii) the need to achieve the lowest feasible wake-up durations, it is important that synchronisation methods be as lightweight and short as possible in the design of a TSP.

3.6.5 Security

Given that LoRa is vulnerable to a number of vulnerabilities, security and privacy are of primary importance as LoRa network growth accelerates. LoRa's physical layer features have exposed novel and potent threats that are difficult to defend, and the protocol's high power efficiency requirement makes developing effective defences much more difficult. Even though the PHY layer security methods can theoretically ensure total security, the lack of robust attributes severely restricts their usefulness. For instance, the majority of current key generation methods only permit the occurrence of two legal parties over a long period of probing, as opposed to group ones. It is difficult for Radio frequency fingerprint identification (RFFI) approaches to account for immediate features that can be used to discriminate between devices and to ensure that freshly joined genuine devices are compatible with the network.

3.7 Summary

This chapter provides a comprehensive literature review of LoRa as an innovative technology within the context of IoT communications. A substantial body of research has been thoroughly reviewed, analyzed, and evaluated, encompassing a wide variety of methods and techniques designed to improve the ADR and TDMA mechanism in LoRaWAN. These studies explore diverse approaches, from machine learning-based prediction models to novel feedback algorithms, all aiming to enhance network capacity, reduce energy consumption, and increase the reliability of data transmission for end-devices. in addition, Summarises the factors and difficulties involved in developing LoRa network protocols for time-slotted medium access. It also analyses the many time-slotted solutions described in the literature, concentrating on open-source protocols with proven simulators and extensive real-world testing. The analysis highlights details on joining methods, scheduling algorithms, synchronizations, and the acknowledgement slot, which have been conducted across a wide range of performance indicators, from acknowledgements to scalability. It also shows how each approach deals with different LoRa parameter values, including SF, BW, CR, and CF. Further, information on the roaming and encryption support provided by these protocols and any information about propagation delay is given. The comparison uncovers several discrepancies, all of which warrant further investigation. Incorporating time-slotted communication has the potential to make LoRa networks a reliable solution for IIoT and other uses. However, many challenges still require further attention, such as minimizing protocol overhead, enhancing battery life, removing security roadblocks and better exploiting the flexibility of LoRa's physical-layer. The next chapter 4 will conduct a new technique called Multi-band Multi-data rate to improve LORaWAN scalability.

Chapter 4

MBMD-LoRa Scalable LoRaWAN for Internet of Things: A Multi-Band Multi-Data Rate Method

4.1 Introduction

LoRa encompasses various link parameters that affect scalability and energy consumption. A node or network manager must choose a suitable configuration to optimise performance (QoS). To conserve energy, the data rate should be optimised while minimising transmit power. Energy savings exceeding 30% can be attained through this method. The slim data rate (SDR) technique enhances data rate results in decreased airtime, allowing for greater capacity for additional nodes and minimising the likelihood of collisions. This results in enhanced scalability of the network. The adjustment of the spreading factor and bandwidth typically results in a reduced data rate, which facilitates concurrent transmissions due to the orthogonality of different spreading factors. Decreasing transmit power also reduces the collision domain. This chapter evaluates the features of the LoRa link parameters utilising the LoRaSIM simulator. The MBMD-LoRa and MBMZ-LoRa algorithms have been developed to optimise a link based on these results. This analysis evaluates the algorithms using metrics including packet delivery ratio, energy consumption/savings, and the proximity to optimality in the node's settings configuration.

4.2 Background

Semtech has developed the LR1121, an ultra-low power LoRa transceiver for the third generation. This device has the ability to establish connectivity through satellite S-Bands, as well as through multi-band LoRa and Long Range - Frequency Hopping Spread Spectrum (LR-FHSS) communication in sub-GHz and 2.4GHz ISM bands[113]. The LR1121 is designed to adhere to the physical layer specifications of the LoRaWAN standard established by the LoRa Alliance. Additionally, it is engineered to be adaptable to meet the needs of different applications and proprietary protocols[72]. LoRa symbol's spectrum bandwidth b is also important; the increment leads to a doubling of the data rate while shrinking the communication range and the BW from 500kHz to 125KHz. It is possible to divide the frequency band into separate bands with different bandwidths that can be adjusted accordingly [114],[1].

In the framework of earlier research, the focus has been primarily on two control parameters, namely SF and transmission power, which are manipulated by the Adaptive Data Rate algorithm to attain reliable and energy-efficient communication across moderate distances. This study assumed the bandwidth as an additional parameter to optimise the node settings in long-distance communication, improve reliability and enhance energy efficiency[115][116]. By leveraging the relationship between the SF and transmission power, the new methods aim to identify the optimal BW and SF setting that minimises ToA and enhances the scalability of LoRa while reducing power consumption.

This chapter presents a model of LoRa networks that includes nodes running with various combinations of Multiband Multi data rate (MBMD) settings. This chapter aims to enhance the scalability of LoRaWAN, which may be served with an acceptable packet delivery ratio probability, considering each frequency band and a specific deployment distance. In order to accomplish this aim, It should optimise the data rate for each spreading factor and bandwidth to minimise the transmission time leads to maximise the overall number of nodes. Firstly, it maximises the usage of airtime, hence optimising the efficiency of data transmission. Secondly, it increases the overall capacity of the communication channel, enabling a greater volume of data to be transmitted within a given time frame. Additionally, adopting short packets helps minimise protocol overhead, resulting in greater efficiency.

This chapter also aims to optimise and improve the performance of LoRaWAN technology through an increase in data rate to minimise the Packet transmission time, as evidenced by the decrease in ToA. On the other hand, the presence of diversity inside a single cell in the context of the SF has a significant influence on mitigating packet collisions. This can be attributed to three main factors.

- The increase in data rate leads to a decrease in the time required for packet transmission (ToA) and less transmission power.
- The small packet size reduces collision occurrences between traffic and saves transmission power from retransmissions.
- One notable contribution is the inclusion of diverse spreading factors within the cellular network. This incorporation serves the purpose of preventing node collisions, hence leading to energy conservation by eliminating the need for packet retransmission.

  The architecture of the LoRa network is described in [75], and illustrated in Figure 2.7. The LoRa network is implemented using a star-of-stars topology, where the exchange of packets between End-Devices(ED) and Gateways is facilitated by the LoRa communication protocol. The related work in this chapter has two directions: the first is LoRaWAN data rate, and the second is Multi-band in LoRaWAN.

4.2.1 LoRaWAN Data Rate

A scalable IoT ecosystem is explored in [117] using LoRaWAN LPWAN technology without considering the packet delivery ratio. The use of

LoRaWAN networks for extensive smart city applications is exemplified by M. Loriot and colleagues [118]. All tests conducted for this study took place at the Scientific Campus of the University of Lille, France. The experiments were conducted to cover distances of up to one hundred kilometers. Other research [119] introduces a method for placing gateways based on graphs. In order to address the difficulty of scalability when installing gateways in very large networks, this study demonstrates that the technique minimises the collision probability and the needed number of gateways while performing similarly to state-of-the-art related work in the worst scenario. The primary Data Rate (DR) parameters encompass the spreading factor, which represents the ratio between the symbol rate and the chirp rate. The SF is directly associated with the communication range and inversely related to the bit rate [115]. The increase in SF leads to a half reduction in bit rate. On the other hand, the increase in bandwidth results in an exact halving of the data rate. Additionally, the bandwidth is another significant parameter, referring to the spectrum occupied by a symbol. The SF is adjustable within a range of 7 to 12, while the BW can be adjusted within a range of 500kHz to 125KHz. This allows for the adaptation of both the communication range and data rate. Lastly, the Coding Rate denotes the rate at which coding is applied [120].

The bit rate of a wireless transmission directly affects the ToA, which is the duration required to send a packet over the wireless channel (packet transmission time). Consequently, the network's complexity is primarily centralised at the NS, which is responsible for managing the transmission parameters (such as spreading factor and transmit power) through the ADR algorithm [121]. Additionally, the NS is responsible for discarding duplicated packets, which are identical data packets received from multiple gateways. Furthermore, the NS selects the appropriate gateway for sending acknowledgements to specific uplink data packets if requested. The bandwidth has a major impact on data rate, especially with the emerging trend of supporting multi-band communications. Semtech, the owner of LoRa, is moving in this direction by introducing some gateways that support multiband technology. However, more research is needed in

Size (bytes)	[2]	[2]	[2]	[2]	[2]	[2]	[3]	[1]
CFList	*ChMask Grp0*	*ChMask Grp1*	*ChMask Grp2*	*ChMask Grp3*	*ChMask Grp4*	*ChMask Grp5*	*RFU*	*CFList Type*

Figure 4.1: EU863-870 Join-Accept Channel Frequency List [1]

this area to further advance it.

4.2.2 LoRaWAN Bands

Researchers [122] have reported on an urban pollution monitoring system. Large-scale modelling and analysis of uplink and downlink channels for LoRa technology in suburban environments using the 915 MHz bands of the LoRaWAN radio channel has been presented [123]. The findings from these experiments indicate that LoRaWAN networks are valuable for implementing applications in smart city settings. Other research [124] proposes a maritime pollution monitoring system that utilises the extensive coverage provided by LoRaWAN communication. This technology extends beyond the limits of an urban area and quantifies contaminants in the ocean. In order to achieve realistic packet rates at the intended scale, the long-range and low power consumption objectives of LPWANs require the implementation of collision avoidance mechanisms due to the inherent low data rate. LoRa addresses this challenge by using a combination of several reception channels at the base station, a variety of supported bandwidths and quasi-orthogonal Spreading Factor coding inside each channel [105][125][126]. The Long-range frequency hopping spread spectrum (LR-FHSS) is a novel physical layer technology developed specifically to address the requirements of extensive communication situations, such as satellite IoT, characterized by significant distances and large-scale coverage. The fundamental aspect of this technology involves the utilization of a rapid frequency hopping method, designed to enhance network capacity while maintaining an equivalent radio link budget to that of LoRa. Moreover, LR-FHSS exhibits effective control over packet transmission due to its inherent design principles, allowing for the implementation of Quality of Service (QoS) regulations at the individual packet level. The research suggest that it is important to comprehend the functioning of LR-FHSS, its potential performance, and its limitations and areas for further research, in light of the extensive use of LoRaWAN in the IoT application domain [113].

The latest version of Semtech's ultra-low power LoRa transceiver is called LR1121. This device offers communication capabilities using multi-band LoRa, Long Range-Frequency Hopping Spread Spectrum (LR-FHSS) technology and supports satellite S-Band connectivity. It works in sub-GHz and 2.4GHz ISM bands, and is designed to follow the physical layer requirements outlined in the LoRaWAN specification released by the LoRa Alliance. Furthermore, LR1121 can be customized to meet various application needs and support unique protocols [72]. EU863-870 Join-Accept CFList of LoRaWAN depicted in Figure 4.1, both CFList Type 0 and Type 1 generate fresh channels for dynamic channel designs. By employing enumeration rather than exact frequencies to describe the additional channels, Type 1 is capable of generating a greater number of channels. Default channels remain unchanged in both scenarios when the CFList is utilised. Default channels can be modified with *NewChannelReq* or disabled with *LinkADRReq* [113]. The 800 MHz fixed channel list specifies 40 channels that can be generated. Channel-ID 0 operates at a frequency of 863.1 MHz, with subsequent channels increasing in 200 kHz increments up to Channel-ID 34 at 869.9 MHz. Five further channels, labelled as 35 to 39, are set at the frequencies 865.0625 MHz, 865.4025 MHz, 865.6025 MHz, 865.785 MHz, and 865.985 MHz. ChMask3, ChMask4, and 504 ChMask5 are still reserved for future use. Based on that, this study assumed a channel frequency plan. The selection of channel frequencies is done in a manner that ensures the absence of any overlap between them within a certain bandwidth. Base stations often possess the capacity to concurrently demodulate and process numerous channels. From a network capacity standpoint, it is possible to see each channel as operating autonomously. Many studies use

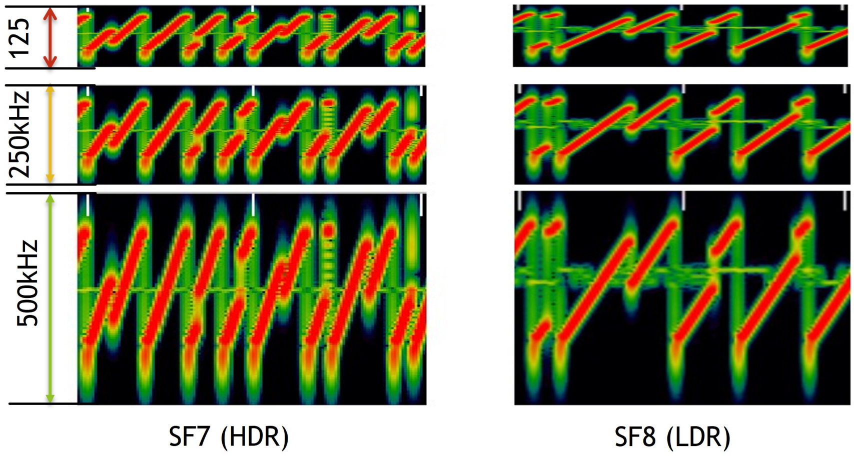


Figure 4.2: Data symbol during different SF and BW

different bandwidths and evaluate their method in terms of scalability. Some studies use 500 kHz bandwidth and evaluate their method in terms of scalability such as [127] [3], other studies use 125 kHz, such as [83] and the researchers in [128] investigated interference between LoRa and IEEE802.15.4g networks including all 125kHz, 250kHz and 500 kHz. The system model discusses the channel frequency plan model.

4.3 System Model for LoRaWAN

The Bit Rate (BR) holds significant importance in the network systems as it plays a decisive role in determining the pace at which data is transferred. Additionally, it directly impacts network performance, ensuring that application requirements are met, optimising the utilisation of available bandwidth, expanding the network's capacity and facilitating technical improvements. The LoRa network bit rate can be calculated using equation 4.1 [129],[120].

$$R_b = f * \frac{b}{2^f} * cr \quad [bits/s] \tag{4.1}$$

Where f is the spreading factor and b is the channel bandwidth and the cr is the coding rate. The spreading factor in LoRa modulation pertains to the quantity of chips employed for encoding each symbol, and it has a direct impact on both the data rate and communication range. The spreading factor f determines the duration of each symbol transmission and the sensitivity to noise. The spectrum of spreading factors in the context of f_7 to $f_1 2$ is characterized by a doubling in symbol duration with each incremental increase in the spreading factor, resulting in a halving of the data rate. The concept of a high spreading factor refers to the utilization of a larger number of chips in a spread spectrum communication system. A spreading factor with a high value, such as $f_1 2$, offers enhanced signal resilience and facilitates long-distance communication. This technology is appropriate for situations that necessitate extensive coverage over great distances, even with the trade-off of reduced data transmission rates. A low spreading factor, exemplified by f_7, is associated with increased data rates but reduced transmission range in comparison to greater spreading factors. Applications that emphasize better data throughput over long-range coverage can benefit from its usefulness. The determination of the suitable spreading factor is contingent upon the particular demands of the application, taking into account several elements like the intended data rate, range, power consumption and susceptibility to interference.

On the contrary, bandwidth pertains to the spectrum of frequencies employed for signal transmission. The data rate in LoRa communication is directly influenced by the bandwidth, as indicated by equation 4.1. The available bandwidth options are commonly set at 125 kHz, 250 kHz, or 500 kHz. Figure 4.2 depicts the variation in bandwidth when different spreading factors are used. The selection of bandwidth has a direct impact on the duration of transmission necessary to convey a symbol, hence influencing the attainable data rate. A narrower bandwidth, such as 125 kHz, facilitates longer symbol lengths, hence enhancing the receiver's sensitivity to weak signals and improving its capacity to discern varying signal levels. Nevertheless, the reduced bandwidth results in a decrease in the attainable data rate. The utilization of a broader bandwidth, such as 500 kHz, leads to a decrease in the time of symbols, hence enabling larger data rates. Nevertheless, broader bandwidths exhibit increased vulnerability to noise and interference, hence compromising the overall signal quality and diminishing the attainable range. Hence, the selection of bandwidth in LoRa necessitates a compromise between the pace at which data is transmitted and the distance over which it may be effectively communicated. Narrower bandwidths are associated with extended transmission distances and enhanced signal resilience, albeit at the cost of diminished data rates. Conversely, wider bandwidths provide higher data rates, however at the detriment of reduced transmission distances and heightened susceptibility to interference. It is crucial to acknowledge that the range of bandwidth possibilities and their associated data rates can differ based on the specific implementation of LoRa technology and the regulatory limitations imposed by different regions. The methodology involved the assumption that the gateway could accommodate many frequency channels, each with its specific bandwidth. Additionally, the determination of the settings for each node is based on their received signal strength indicator (RSSI) and signal-to-noise ratio (SNR) and considers the sensitivity of the gateway.

4.3.1 Link and Propagation Model

The link budget of a wireless system or network refers to the comprehensive assessment of the total gains and losses incurred during the transmission process, encompassing the transmitter, propagation channel and the intended receiver. The gains and losses encompass several factors such as system gains and losses related to the antenna, matching networks, and other components, as well as losses linked with the propagation channel itself, which can be determined using either modelling or observed data. In general, when considering channel mechanisms that exhibit random variations, such as multipath and

Doppler fading, it is customary to incorporate supplementary margin based on the expected severity. The link budget for a wireless network link can be mathematically represented in equation 4.2 in [120] as follows:

$$P_{rx}(dBm) = P_{tx}(dBm) + G(dB) + PL(dB) \tag{4.2}$$

WhereP_{rx} is receiving power, the P_{tx} is transmission power, $G(dB)$ is the antenna gain of transmitter and receiver, and the $PL(dB)$ is the path loss. All gains can be collected and written as equation 4.3 [120]:

$$G(dB) = G_{tx}(dB) + G_{rx}(dB) \tag{4.3}$$

while the all-path loss is represented in equation 4.4 [120]:

$$PL_{Total}(dB) = PL_{Env} + PL_{tx}(dB) + PL_{rx}(db) - X_{\sigma} \tag{4.4}$$

With $G_{tx}(dB)$,$PL_{tx}(dB)$,$G_{tx}(dB)$ and $PL_{rx}(dB)$ plus minus set to zero, X_{σ} is the fading margin while $PL_{Env}(dB)$ is dictated by the communication environment. Different surroundings (urban, suburban) affect route loss in several models. The popular log-distance path loss model [130] is employed to model the deployments in heavily populated areas. This architecture has been chosen because it suits LoRa deployment scenarios. This model describes path loss as a function of communication distance d as in equation 4.5:

$$PL_{Env}(d) = PL_{Env}(d_0) + 10_{\lambda} log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma} \tag{4.5}$$

$PL_{Env}(d)$ represents the path loss in dB, $PL_{Env}(d_0)$ signifies the average path loss at the reference distance d_0, λ denotes the path loss exponent and X_{σ} $N(0, \sigma^2)$ represents the normal distribution adjusted for shadowing with a mean and a variance of zero with a 95% confidence interval. Additionally, the simulations conducted using the settings documented by Martin Bor[131], Mariusz Slabicki[80] and [132] demonstrated comparable outcomes in relation to scalability. Moreover, a novel channel frequency plan has been conducted in more detail in the next section.

4.3.2 Channel Model

LoRa technology operates in the frequency range of 137 to 1020 MHz. This frequency range is divided into multiple frequency bands, and the specific bands used may vary depending on regional regulations and the LoRa implementation being used. The available frequency bands for LoRa communication include, but are not limited to, 433 MHz, 868 MHz, and 915 MHz[1]. These frequency bands were selected to provide optimal coverage and propagation characteristics for long-range communication while complying with regulatory requirements in different parts of the world. It is relatively easy for cities or IoT providers to use LoRa because these frequency bands are available as free licences. In addition, in the UK LoRa can operate in 433.05-434.79 MHz, 863-873MHz and 915-928MHz [1]. Moreover, LoRa can operate on 125 kHz and 500 kHz bandwidths in the US, while in the EU on 125 kHz and 250 kHz bandwidths. Channel plans for the US915–928 band are as follows: Starting at 915.2 MHz and increasing linearly by 200 kHz to 927.8 MHz, there are 64 channels upstream, numbered 0 to 63, that use LoRa 125 kHz BW. The channels range from DR0 to DR5, and the coding rate is 4/5. Eight upstream channels, numbered 64–71, using LoRa 500 kHz BW at DR6 or LRFHSS 1.523 MHz BW at DR7, progress incrementally by 1.6 MHz from 915.9 MHz to 927.1 MHz, while the downlink channel starts at 923.3 MHz and increases linearly by 600 kHz to 927.5 MHz. There are 8 channels numbered 0 through 7 that use LoRa 500 kHz BW at DR8 to DR13. EU863-870 band LoRaWAN includes a Channel Frequency List of 16 octets in the Join Accept message for both $CFList$ Type 0 and $CFList$ Type1, as seen in the diagram. Upon receiving a $CFList$ Type 1, it must be read in accordance with the channel list description.

The 800 MHz fixed channel list specifies 40 channels that can be generated. Channel-ID 0 is at a frequency of 863.1 MHz, with channels increasing at 200 kHz intervals up to Channel-ID 34 at 869.9 MHz. Five further channels, labelled as 35 to 39, are set at frequencies of 865.0625 MHz, 865.4025 MHz, 865.6025 MHz, 865.785 MHz, and 865.985 MHz. $ChMask3$, $ChMask4$, and $ChMask5$ are reserved for future usage (RFU). Both $CFList$ Type 0 and Type 1 generate new channels for dynamic channel designs. Type 1 can generate a greater number of channels due to a more concise description of the extra channels using enumeration instead of specific frequencies. Default channels remain unchanged when the CFList is applied in both scenarios. Default channels can be deactivated using $LinkADRReq$ or adjusted using $NewChannelReq$ [1]. The mechanism for self-adapting channel rate planning and differential service is based on frequency division, as described in [133]. Accordingly, this study in this Chapter assumes the LoRa Multi-bandwith frequency channels plan as shown in Table 4.1.

Table 4.1: Assumed channels utilised setting in the simulations

Index of Channel	Frequency(MHz)	No.of Received Paths	Allocated Bandwidth
1	868.10,868.30,868.50	3	125
2	863.2-865	3	250
3	867.5,872.1	2	500

4.3.3 Simulation Model

There are multiple factors that affect whether a receiver can decode one or two packets, or none at all, when two LoRa signals collide. These factors include Carrier Frequency, Spreading Factor, voltage, and duration. The collision between packets p_1 and p_2 happens only when all the conditions defined as in equations 4.3.3 are met:

$$C_{pckt}(p_1, p_2) =$$

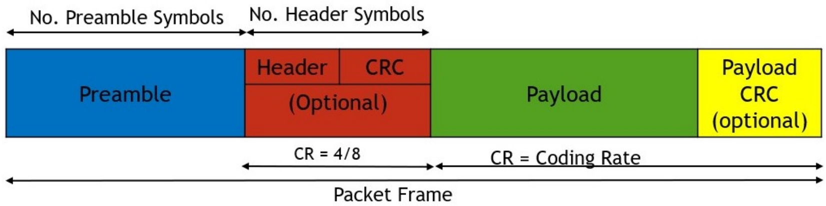


Figure 4.3: LoRa Packet Formatting.

$$\begin{cases} 1 & if \quad (O(p_1,p_2) \wedge C_{fr}(p_1,p_2) \wedge C_f(p_1,p_2) \wedge C_{pw}(p_1,p_2) \wedge C_t(p_1,p_2)) \\ 0 & \text{else} \end{cases} \tag{4.6}$$

The situation in which two transmissions collide on $C_{fr}(p_1, p_2)$ may be defined by considering the centre frequencies of transmission (p_1, p_2), denoted asfr_1 andfr_2 respectively. Additionally, the least allowable frequency offset is represented by a threshold. Semtech SX1272 has a minimum acceptable frequency deviation of 60kHz when using a bandwidth of 125kHz, 120kHz when using a bandwidth of 250kHz, and 240kHz when using a bandwidth of 500kHz. The orthogonal Spreading factors $C_f(p_1, p_2)$ are employed in this case. Therefore, it is possible to correctly decode transmissions that have different SF (while maintaining the same CF and BW), provided that there are two accessible receiver pathways. $C_{pw}(p_1, p_2)$ occur When two signals are present at the receiver, where the stronger signal suppresses the weaker signal. Thus, the received signal intensity may vary by a small degree. However, when the difference is too slight, the receiver switches between the two signals and is unable to decipher either, where the two packets are denoted as (p_1, p_2). The expression $O(p_1, p_2)$ represents the time complexity of a function or algorithm in terms of two variables (p_1, p_2) when the periods of their reception overlap. In order for the receiver to recognise the preamble and synchronise, it requires five symbols. Eight preamble symbols were included in the broadcasts. Hence, the receiver looks at the weak transmission after three symbols, but the strong transmission suppresses its signal, corrupting the packet. It may be inferred that packets can overlap if, in the event of a weak packet, at least five preamble symbols remain undamaged (i.e. the most important part of a packet's receipt begins with the final five preamble symbols). Figure 4.3 illustrates the packet structure and the equations 4.7, 4.8 and 4.9 show how the time preamble, the simple time symbol time and the number or length preamble are calculated, respectively.

$$T_{\text{preamble}}(f) = (L_{\text{preamble}} + 4.25) \cdot T_{\text{symbol}}(f) \tag{4.7}$$

$$T_{\text{sym}}(f) = \frac{2^f}{b} \tag{4.8}$$

$$L_{\text{preamble}} = \left(\frac{2^f \times 12.25}{b}\right) + \left\{8 + \max\left(\text{ceil}\left(\frac{8PL - 4f + 28 + 16CRC - 20IH}{4(f - 2DE)}\right)(\text{CR}+4),\, 0\right\}\right. \tag{4.9}$$

Given the dependencies provided, the variable PL represents the quantity of payload bytes. The abbreviations f and b represent the concepts of the spreading factor and bandwidth, respectively. The value of H is 0 when the header is enabled and 1 when no header exists. When the low data rate optimization is enabled, the value of DE is 1. Conversely, when the optimisation is removed, the value of DE is 0. The coding rate ranges from 1 to 4. It may be inferred that if there is a need to decrease the duration of airtime and the length of the packet is predetermined, then the header data can be omitted. The duration of the payload can be calculated by multiplying the symbol period by the total number of payload symbols.

The sensitivity of the gateway and end device receivers for a given spreading factor can be denoted as $S_G(i)$ and $S_e(i)$ in decibels (dB), respectively. According to [72], observation reveals that augmentation of SF results in improved sensitivity, with consistent increments of 2.8 dB, while decreasing BW from wider bandwidth to narrow bandwidth results in improved sensitivity, from 3 to 4 dB. For Downlink (DL) transmissions, the consideration of the sensitivity of an end device is expected to be lower than that of a gateway by introducing a 3 dB offset. Sensitivity values are utilised to ascertain whether a packet is detected by a device. The sensitivities are represented by equation 4.10 given in [72].

$$S_{(f,b)} = -174 + 10log_{10}b + NF + SNR_f \tag{4.10}$$

The first term is a result of thermal noise within a bandwidth of 1 Hz and can only be altered by modifying the temperature of the receiver. The second term, b, refers to the bandwidth of the receiver. NF is the receiver noise figure, which is a constant value that remains unchanged for a specific hardware implementation. The term SNR represents the signal-to-noise ratio that is necessary for the underlying modulation technique.

$$P_{rx} > S_{f,b} \tag{4.11}$$

If the power of a signal with a spreading factor f of i at the receiver's location falls below the threshold Sg(i), it cannot be detected by the gateway. Conversely, it can be detected if the received power exceeds the necessary sensitivity. In this scenario, also presume that the recipient synchronises with the incoming signal and commences the reception of the packet. This suggests that once a packet is received with sufficient power to initiate detection, it will remain detectable (i.e., over the sensitivity threshold) until it is fully received. If multiple signals with individual powers below the sensitivity threshold arrive simultaneously at the receiving antenna, they cannot be recognised by the receiver, even if their combined power is above the sensitivity threshold, and a collision might have happened between packets.

4.4 Multi-Band Muti-Data Rate for LoRaWAN

4.4.1 Slim Data Rate

This technique assumes that a set of N nodes exists that are random dispersed across an area with a radius of D, centred around a single gateway. It also considered the gateway supports multi-bandwidth simultaneously by dividing the eight channels as follows: two channels using 500kHz, three channels using 250kHz, and three channels using 125kHz as illustrated in Table 4.1. Even if this assumption is not accurate, however, it is logical and possible because each individual node has individual settings, including bandwidth, channel frequency and spreading factor. In addition, the new version of LoRa supports a new spreading factor and new frequency bands [72]. Given the hypothetical scenario where the gateway is equipped with three fundamental channels that possess unique bandwidth and a set of sub-channels, each individual node is required to transmit data within a certain time window, denoted as T_t, for the purpose of data collection. This study aims to quantify the mean likelihood of achieving successful packet reception for each spreading factor and bandwidth combination. The LoRa MAC layer is based on ALOHA MAC protocol that operates without acknowledgements. It is assumed that the nodes transmit packets autonomously, without any dependence on each other, or on their geographical locations. The proportion of nodes configured with spreading factor f is given in [74].

$$\sum_{f=7}^{12} \beta_f = 1 \quad \forall f \in SFs \tag{4.12}$$

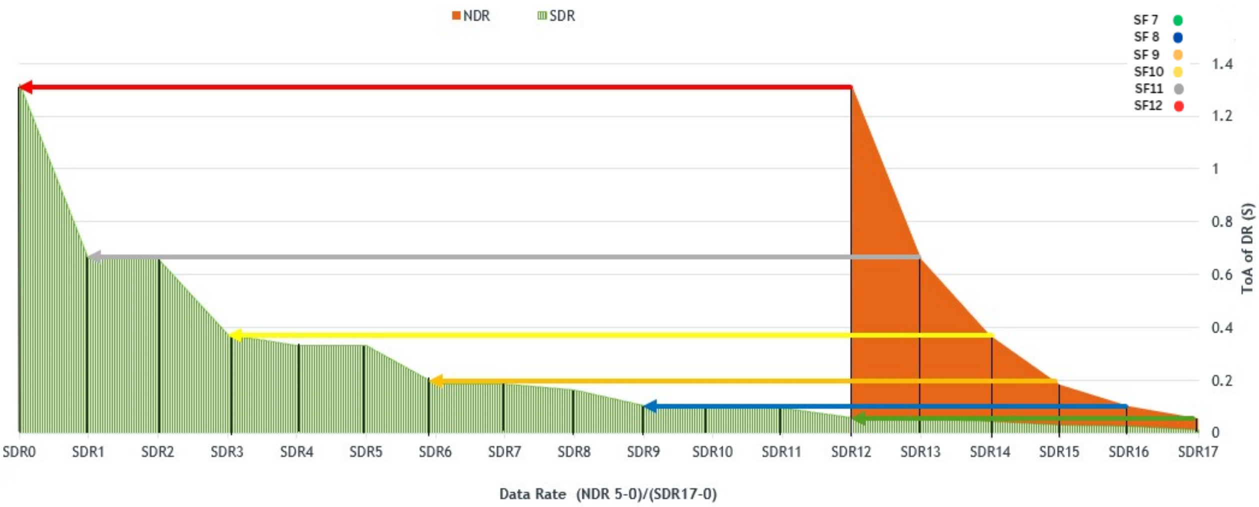


Figure 4.4: Normal Data Rate vs Slim Data Rate.

where f ranges from 7 to 12. Accordingly, the proportion of nodes configured with bandWidth b is given by the following equation.

$$\sum_{b=1}^{3} \alpha_b = 1 \quad \forall b \in BWs \tag{4.13}$$

where b from 1 to 3 refer to bandwidths 500,250 and 125 kHz. A packet production at the deployment area of nodes follows a Poisson distribution, with rate ${}_fN$ in all zones of spreading factors $zone_f$. Suppose a node located at a distance d_i from the gateway, which is transmitting messages μ with a spreading factor of f. Considering the phenomenon of the capture effect, the successful transmission of a packet by a node can be determined by two conditions: (a) the absence of any other packet with the same spreading factor overlapping with the current packet within the same receiving time t_r, or (b) the power level at the gateway of any other packet with the same SF surpassing the power level of the current packet by a minimum threshold value PW_{thld} [131]. Given the assumption of uniform transmission parameters across all nodes, the potential sources of interference can be identified based on the path-loss characteristics of the signal. Specifically, all nodes located at a distance of d_i from the gateway, where maximum distance is defined by the equation 4.14

$$D = d_0 * 10^{\frac{PL_{env}}{10\lambda}} \tag{4.14}$$

where λ represents the path loss exponent, therefore, from assuming a uniform distribution of nodes with spreading factor f, the total number of possible interferers may be calculated $\beta f N \frac{(min(d_i,D)^2}{D^2}$ where D is the maximum distance (range). The probability of successful transmission is $P_s(d)$. Ensuring that no potential interfering nodes initiate a transmission during a vulnerability period of 2Tf is crucial to maintaining a secure and reliable system.

$$P_s(d) = e^{-2T_f \mu \beta_f N(\frac{(min(d_i,D))^2}{D^2})} \tag{4.15}$$

The slim data rates are derived from equation 4.1. The likelihood of success data rate is derived from the equation introduced in [74].

$$Pc_f = \frac{f}{2^f} / \sum_{i=7}^{12} \frac{i}{2^i} \quad \forall f \in SFs \tag{4.16}$$

However, a significant limitation of equation (4.17) is that it does not consider bandwidth b and coding rate variables, and equation (4.12) does not consider the SF. In order to accurately predict the success probability of this method, it's important to take into account the effect of two crucial factors: bandwidth and spreading factor. By accounting for the impact of BW and SF on the success probability ensures that these methods are optimized for maximum efficiency and efficacy. This accounting for BW and SF is the main contribution of the research work conducted and reported in this chapter.

From equations (4.13) and (4.12), the success probability $P_s(d)$ and throughput Tht as follow equations 4.17 and 4.18 respectively:

$$P_s(d) = e^{-2T_f \mu \beta_f \alpha_b (N \frac{(min(d_i,D))^2}{D^2})} \tag{4.17}$$

$$Tht = \frac{P_s * P_L * N}{\tau} \tag{4.18}$$

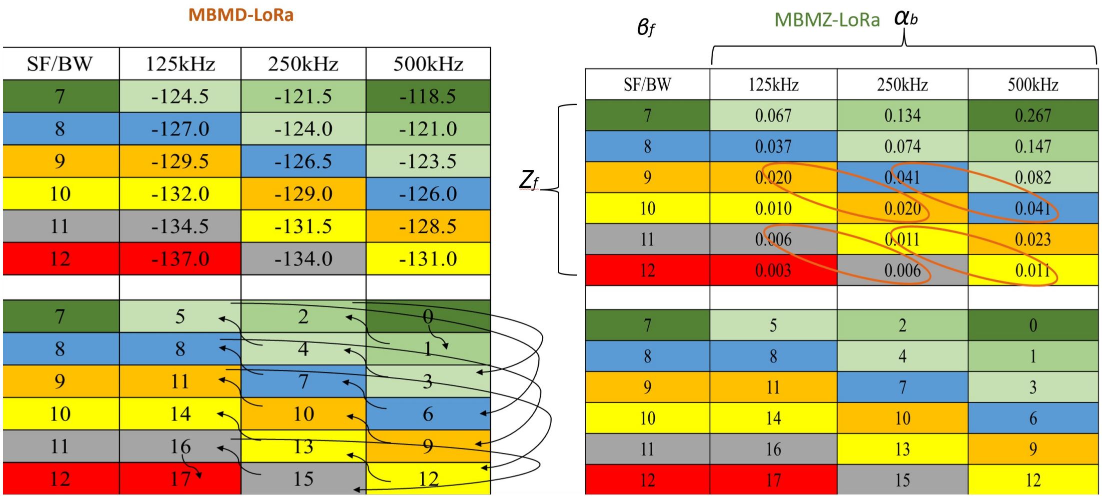


Figure 4.5: MBMD-LoRa And MBMZ-LoRa technique to grant the setting.

where P_L is the data payload and N is the number of EDs, while the collision probability $P_{f,b}$ will be expressed by equation 4.19.

$$P_{f,b} = \frac{p_f * b}{\sum_{i \in BWs} i} \quad \forall f \in SFs \& b \in BWs \tag{4.19}$$

Moreover, considering multiple channel frequencies, the equation becomes as equation 4.20:

$$P_{f,b,cr} = \frac{p_{f,b} * ch}{\sum_{i \in CHs} i} \forall f \in SFs \& b \in BWs \& ch \in CHs, \tag{4.20}$$

4.4.2 MBMD-LoRa Algorithm

The MBMD-LoRa algorithm 1 is proposed in this section. The initial step in establishing a connection between the nodes and the gateway involves utilising default settings, which entail a high spreading factor, narrow bandwidth and a small code rate. During this connection process, the gateway receives a substantial amount of information from the nodes, including SNR, $RSSI$, and various other settings, which are transferred

Algorithm 1 MBMD-LoRa algorithm

Input : n List of N nodes, Md Max distance.

Output: Ch, TP, SF, BW, CR, settings for each i of the N nodes ToAi and k for each zone Processed list.

```
1  Sort: N corresponding distance di by Ploss, RSSI, Z deployment zones.
2  PtxLevel = [ ], SF = [ ], BW = [ ], Ch = [ ], Zone = [ ], Se = [ , ] Set[SF ,
   BW,Cr ]
   /* Assign settings to each node in the list of N nodes.          */
3  while i ≤ N do
4      if RSSI[i] > MinSens then
5          for j ← 0 to MDR do
               /* assign parameters setting to set[i] .              */
6              if RSSI[i] > Sen[j] then
7                  SFi ← fj
                    BWi ← bj
                    Chi ← Chz
                    ToAi ← ToA(Sj, Bk, CR)

8              end
9          end
10     else
           // Update Node's Transmission power
11         TP[i] = TPwLevel[]+ = 1
            RSSI[i] = TP[i] − PLoss + GN
            Go to step 6
12         Eng[i] ← CalculateEnergy

13     end
14     TotalEng = Sum(Eng[i])
        i+ = 1
        return Setting of Each Node and The Average of Energy Consumption per Node
```

to the network server. Firstly, NS define transmission power levels as shown in the MBMD-LoRa Algorithm 1 $P_{tx}level$, SF, BW, and Ch, then lists the settings depending on the number of SDRs, as illustrated in Figure 4.4. Secondly, the NS sorts the nodes depending on d distance and $PLoss$. Subsequently, as illustrated from row 5 to row 13, the algorithm proceeds to evaluate the connection and link budget by comparing the nodes' RSSI values to the gateway's sensitivity. Based on the node's link budget and its $RSSI$, the best setting will be selected from multiple configuration settings $Set[SF, BW, Cr]$, which is predefined. If the node's $RSSI$ is not more than the gateway sensitivity, the algorithm increases the transmission power of that node as in steps 15 to 19, then reassesses the node's link budget as in row 6 to obtain the suitable setting set_i for the node and so on. The main objective is to select the optimal setting that ensures a reliable connection while minimising power consumption. In this algorithm, the selection of node configuration is not solely based on spreading factor and Transmission Power (TP) as in conventional methods. Instead, the slim data rate is incorporated, which takes into account both the spreading factor and bandwidth, in addition to the slim TP_i steps. The algorithm aims to achieve high scalability and minimise energy consumption. Figure 4.4 visually represents the distinction between the normal slim data rates. MBMD-LoRa grants the settings based on data rate order, while MBMZ grants the settings based on zone capacity for node configurations in that zone, as illustrated in the Figure 4.5, those algoritms can be applicable in healthcare such coronavirus pandemic, or anther IoT applications such as smart home, smart city etc.

4.4.3 MBMZ-LoRa algorithm

The MBMZ algorithm is designed based on MBMD to determine the optimal route and rank for a novel agile data rate, with the objective of establishing a reliable and efficient connection. The network server initiates the assessment of the Received Signal Strength Indicator (RSSI) of nodes and compares it with gateway sensitivity then assigns them the configuration that aligns with the specific circumstances of each node and assigns that nod to the proposed zone by increasing the value of k in zone B_f. If the node's $RSSI$ is not more than the gateway sensitivity, the algorithm increases the transmission power of that node as in steps 15 to 19, then the node's link budget occurs as in row 6 to obtain the suitable setting set_i for the node, and so on. The use of diverse transmission characteristics, such as spreading factor and bandwidth leads to different data rates and the consequent airtime. As a result, the disparity in airtime allocation results in differing collision probabilities, hence creating an unfair distribution of resources among nodes inside a certain zone. The MBMZ-LoRa algorithm 2 is proposed using β_f and α_b to ensure fair distribution and enhance the packet delivery ratio based on ζ which is the result of multiplication of equations (4.13) and (4.12), and presents the number of slim data rate ζ in rows [0, 17]. As noted, the algorithm is checks if the number of nodes in Zone Z_f assigned to spreading factor$f$ is not more than the β_f value, otherwise, a move to fulfil the next zone Z_{f+1} is made, and so on, based on the following equations:

$$\sum_{i=7}^{12} Zone_f = 1 \quad \forall f \in SFs \tag{4.21}$$

$$\sum_{i=7}^{12} \beta_f \sum_{i=1}^{3} \alpha_b = 1 \quad \forall f \in SFs, \forall b \in BWs \tag{4.22}$$

MBMD-LoRa and MBMZ-LoRa, aim to improve LoRaWAN, where the data rate doubling is intended to reduce the packet transmission time, leading to fewer collisions and less transmission power. On the other hand, the degree of diversity in SF within a single cell significantly influences the ability of $Pckt$ to avoid collisions. These methods achieve greater energy efficiency, initially due to the fact that an increase in data rate results in a reduction in $Pckt$ time, in addition to a decrease in collisions caused by $Pckt$ size, which reduces transmission power and retransmission for $Pckt$.

Algorithm 2 MBMZ-algorithm

Input : n List of N nodes corresponding distance D by $PLoss$, $RSSI$, Z deployment zones.

Output: Ch, TP, SF, BW, CR settings for each i of the N nodesToA_i and k for each zone Processed list.

$PtxLevel = [\ ], SF = [\ ], B = [\ ], Ch = [\ ], Zone = [\ ], Se = [\ ,\ ]$ $Set[]$ = [S , B,C ,TP , ,]

`/* Assign settings to each node in the list of N nodes. */`

while $i \leq N$ **do**
    if $RSSI[i] > MinSens$ **then**
        for $j \leftarrow 0$ **to** MDR **do**
            `/* assign parameters setting to set[i] . */`
            if $RSSI[i] > Sen[j]$ **then**
                if $Z_f > \beta_f$ **then**
                    $SFi \leftarrow fj$
                    $BWi \leftarrow bj$
                    $Chi \leftarrow Chz$
                    $ToAi \leftarrow ToA(Sj, Bk, CR)$ $Z_f.append([k] + 1)$ `// count n in each zone.`
                else
                    $Z_f = Z_f + 1$
                    $\beta_f = \beta_f + 1$
                end
            end
        end
    else
        `// Update Node's Transmission power`
        $TP[i] = TPwLevel[] += 1$ $RSSI[i] = TPwLevel[] - PLoss + GN$
        Go to step 6Eng[i]$\leftarrow$ *CalculateEnergy*
    end
    $TotalEng = Sum(Eng[i])$
    $i += 1$
end
end
return
Setting of Each Node and The Average of Energy Consumption and Node's zone

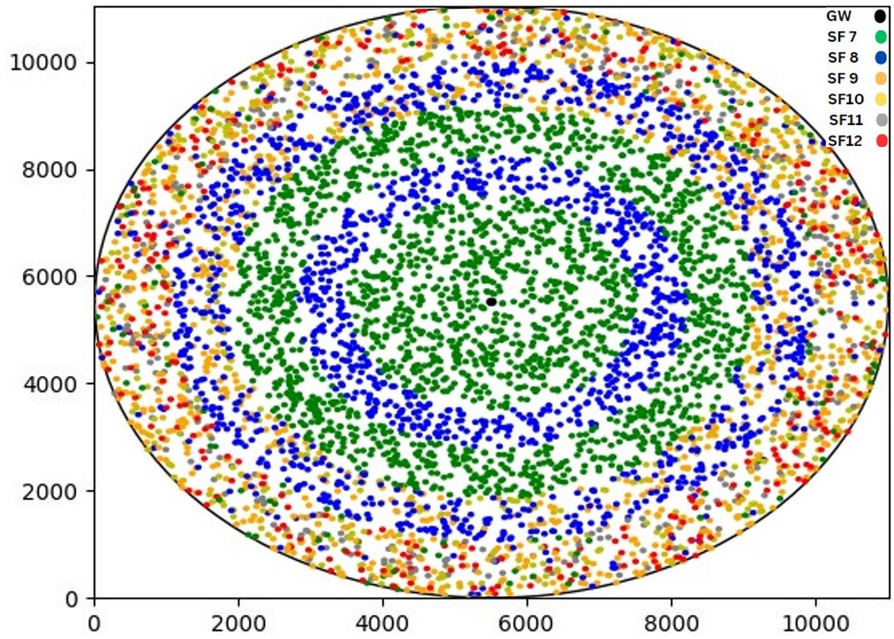


Figure 4.6: LoRa Network Deployment based on spreading factor.

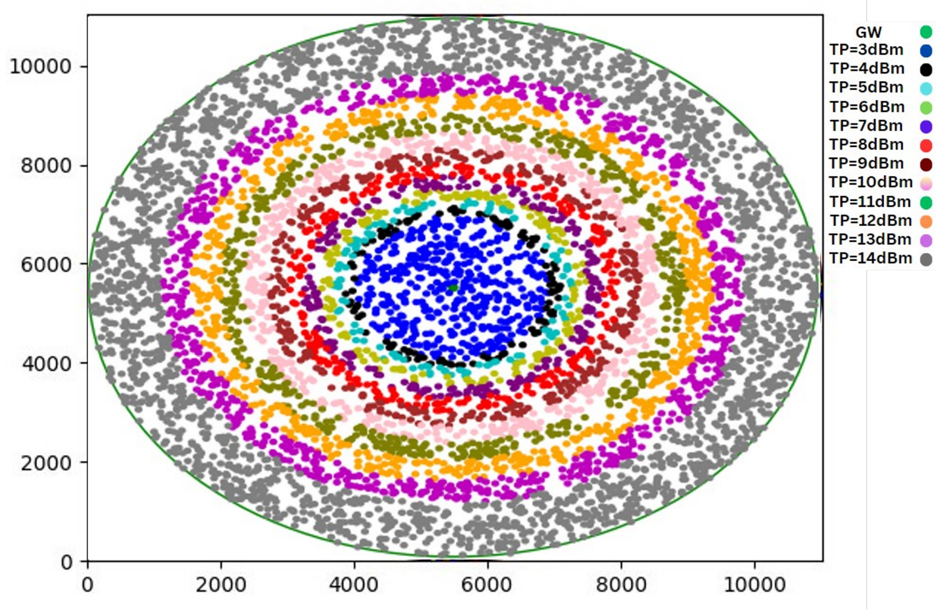


Figure 4.7: LoRa Network Deployment based on transmission power.

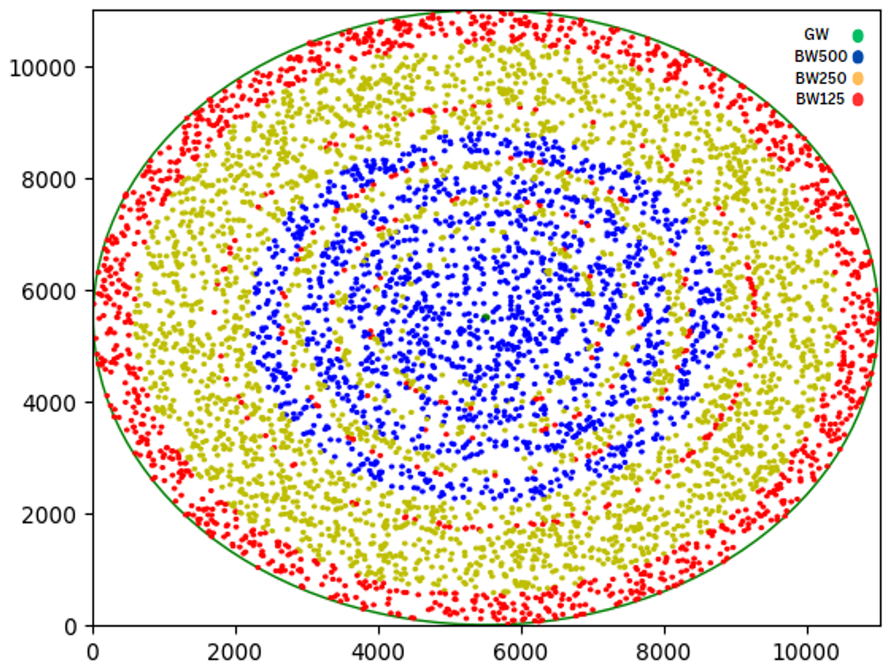


Figure 4.8: LoRa Network Deployment on ZBMD.

4.5 Performance Evaluation

The effectiveness of these proposed resource allocation solutions, which are based on the MBMD-LoRa and MBMZ-LoRa algorithms, are illustrated in this section. The evaluation of their performance uses the LoRaSim, a discrete-event simulator developed by Bor et al.[131], which uses the Simpy library to analyze scalability and collision issues in LoRa networks. Python 3.9 version is utilized to construct the simulations. Two distinct methods have been created that mainly vary in the allocation of SFs, where specifically the MBMD-LoRa method is random-zone without β_f distribution, and the MBMZ-LoRa method is β_f based on six distributed zones Z_f. Given that the novel methods are designed for large-scale dense networks, the simulations were conducted with a substantial number of nodes, ranging from 500 to 6000. These nodes were randomly dispersed throughout an 11 km^2 geographical area. In addition, the scenario assumed the presence of a LoRa network with one gateway positioned at the centre of the region. In terms of packet size, each node produces packets that are 50 bytes in size. The duration between the arrival of consecutive packets follows an exponential distribution with a mean of 600 seconds. Like [81], the European regional specifications for the LoRa physical layer are employed, with a 1% duty cycle for both the LoRa nodes and the gateway. Table 4.2 presents a summary of the utilised simulation parameter values. The analysis and comparison of the effectiveness of these methods with LoRaWAN's ADR algorithm has been conducted. This evaluation is based on the assessment of collision probability, throughput and packet delivery ratio.

Table 4.2: System parameters used in evaluation

Parameter	Value	Comments
N	500 - 6000	Network Size
f	7 to 12	Spreading Factors
$d0$	1000 m	Initial Distance
λ	2.32 dBm	$PLoss$ Exponent
$PL_{Env}(d0)$	128.95	PLoss of Initial Distance
$TPLevel$	2 dBm to 14 dBm	Transmission Power
cr	4/5	Coding Rate
b	[125,250,500]kHz	Bandwidth
MD(R)	5500 m	Field Radius
CF	[860, 864, 868]	Carrier Frequency(MHz)
T(s)	One day	Simulation Time
τ	10 min	Round Time

MBMD-LoRa framework aims to optimise and improve the performance of LoRaWAN technology. As shown in Table 4.3, the Data Rate DR0 exhibits little alteration, whereas DR1 to DR5 demonstrate a discernible augmentation. The data rate in DR1 rose by around 48 bits per second. In comparison, DR2 exhibits a four-fold increase in data rate relative to DR1. Subsequently, the trend of doubling the data rate continues from DR2 to DR5. This increase in data rate has led to minimising the packet size on the air, as evidenced by the decrease in ToA and transmission time. On the other hand, the presence of diversity inside a single zone in the context of spreading factors has a significant influence on mitigating packet collisions.

The proposed methods have achieved higher energy efficiency. This can be attributed to two main factors. Firstly, the increase in data rate results in a decrease in the time required for packet transmission (ToA). Secondly, the reduced collision occurrence owing to packet size leads to lower transmission power and fewer packet retransmissions. One notable contribution is the inclusion of diverse SF within the cellular network. This incorporation serves the purpose of preventing node collisions, hence leading to energy conservation by eliminating the need for packet retransmission.

The algorithm underwent evaluation through comparison with both the standard solution in the field and an alternative method described in previous literature [131], and best equal power (BE-LoRa) [79]. This evaluation employed an integrated methodology that encompassed both simulations and tests. A specific experimental setup consisting of a single ED transmitting data to a GW, which is connected to an NS, was employed to analyse the Packet delivered ratio by various networks, including both urban deployment areas and suburban deployment areas. The evaluation of MBMD-LoRa and MBMZ-LoRa has been conducted under the assumption that the LoRaWAN Gateway has the capability to handle several bands simultaneously in terms of network throughput, energy efficiency by SF, BW utilisation and TP Level utilisation. All experiments were run for a real-time of one day and repeated 10 times with different random seeds.

Table 4.3: The enhancement in LoRaWAN Data Rate For EU 862-872

DR	SDR	BW(kHz)	SF	Bit Rate [bit/s]	Increament [bit/s]
0	0	125	12	293	0
1	1,2	125→ 250	11,12	537-585	48
2	3,4,5	125→ 500	10,11,12	976-1172	196
3	6,7,8	125→ 500	9,10,11	1757-2148	391
4	9,10,11	125→ 500	8,9,10	3125-3906	781
5	11→ 17	125→ 500	7,8,9	5468-7031	1563
6	6,7	125→ 500	7,8,9	5468-7031	1563

The mathematical calculation reveals that there are 2 NDRs and 11 SDRs within the time period of 0 to 0.2 seconds. Similarly, within the time interval of 0.2 to 0.63 seconds, there are 2 NDRs and 5 SDRs. The marginal rise in SDR enables nodes to use the variety of data rates present in SF and BW to obtain the lowest possible ToA, ensuring a dependable connection and reducing transmission power usage. All experiments were run for a real-time of one day and repeated 10 times with different random seeds.

4.5.1 Packet Deliver Rate (PDR)

The Packet Delivery Ratio is defined as the quotient of the total number of received packets higher than the gateway sensitivity. According to Figure 4.9, the PDR of the MBMD-LoRa scenario in the proposed method is much higher than the PDR of BE-LoRa and LoRaWAN. More precisely, the PDR of theB_f-based scenario is four times higher than the PDR of LoRaWAN when there are 6000 nodes. A B_f-based scenario provides lower spreading factors to nodes that are close to the gateway to exploit every level of slim data rate and ToA of packets, which is why it achieved high PDR. Also, the Non $B_f$scenario employs the same selection strategy of SF from the pool of eligible SFs without zone Caritra. As a result, nodes located at the periphery of the zone may be allocated low SFs leading to their transmissions being received at the gateway with a signal strength below the sensitivity threshold as illustrated in Figure 4.6. Consequently, this will result in a fall in the PDR. BE-LoRa has a significant reliance on high spreading factors, particularly SF 12, which resulted in lengthy data packets and lengthy transmission times, which accelerated collision rates and decreased data delivery. Concerning LoRaWAN, the network server of LoRaWAN adjusts the spreading factors and power levels utilised by the nodes based on statistical data gathered from previously received packets. This process leads to slower and less precise updates, resulting in lower packet delivery ratios.

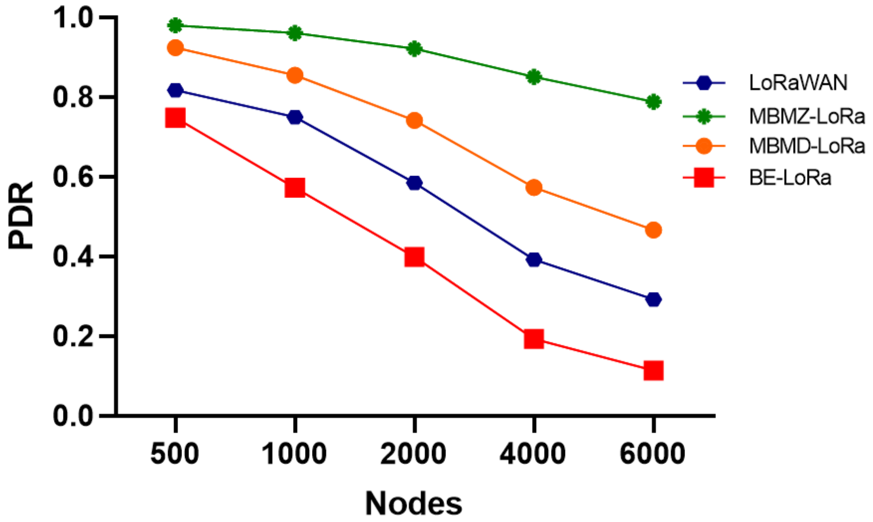


Figure 4.9: Packet Delivery Ratio

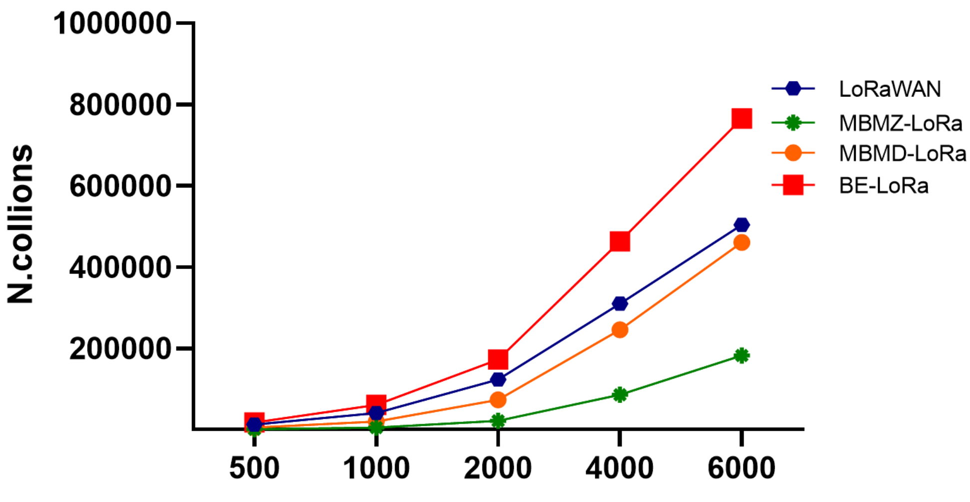


Figure 4.10: The Collisions Probability

4.5.2 Collision

Figure 4.10 illustrates the relationship between the number of nodes and the chance of collision. The likelihood of a collision for all protocols increases as the number of nodes and traffic rate rise. It is important to note that both versions of this method attain a reduced likelihood of collision compared to BE-LoRa and LoRaWAN. This is due to the effective dissemination of transmission parameters among the nodes. BE-LoRa typically assigns SF12 to the majority of nodes as shown in Figure 4.11. In addition, LoRaWAN exclusively utilises the default channels and does not take advantage of the multi-channel capability of the LoRa physical layer. As a result, all nodes have a tendency to communicate on the same channel, leading to a higher occurrence of collisions. Moreover, the heavy reliance of BE-LoRa on high spreading factors, particularly SF 12, 11, and 10, results in the generation of large data packets and thus, long transmission times. This, in turn, leads to a higher occurrence of collisions. Concerning the suggested methods, the Multi-Band Multi-Data Rate scenario achieves a reduced collision probability compared to the random scenario due to the sub-cell distribution mechanism. These mechanisms ensure a sim-equal distribution of SFs across the nodes, as shown in Figure 4.11.

4.5.3 Throughput

Figure 4.12 illustrates the network throughput as a variable dependent on the number of EDs. The performance in this instance is a direct result of the conduct of the PDR. For small values of Nodes, the Tht grows proportionally with it, as indicated by equation 4.18. This leads to a high PDR. However, when the network size becomes excessively large through increasing in used nodes (N), the PDR starts to decrease significantly, causing a saturation effect on the Throughput. Hence, the enhancement of the suggested solutions in comparison to the conventional one is amplified by augmenting the quantity of EDs.To begin with, it is important to note

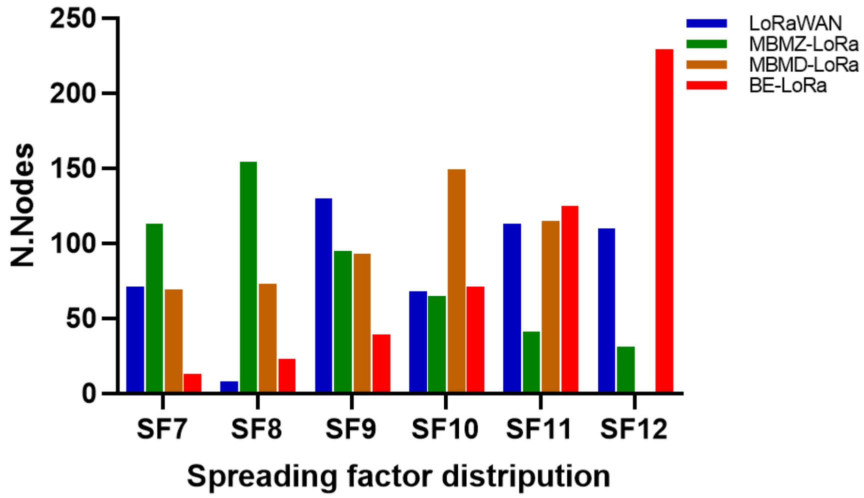


Figure 4.11: Spreading Factor distribution as a function of No.nodes

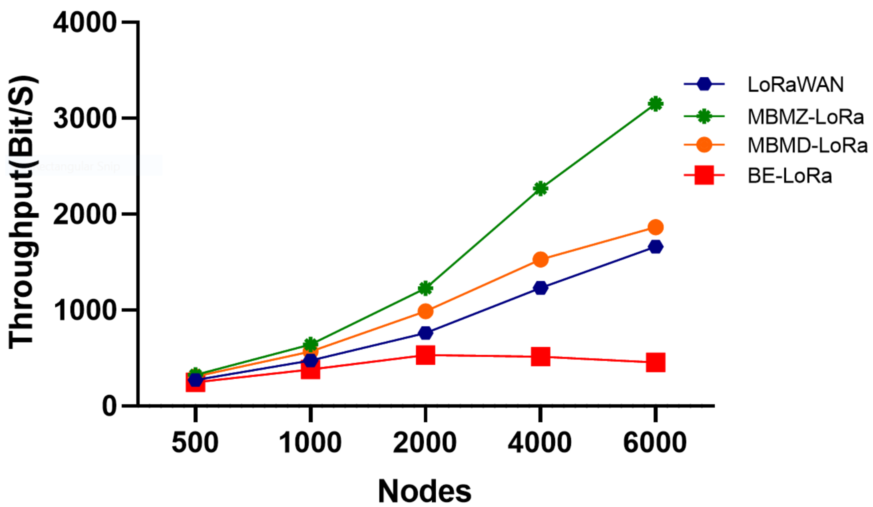


Figure 4.12: The throughput as a function of No.nodes

that both iterations of this algorithm attain superior data transfer rates compared to LoRaWAN. Furthermore, it should be observed that the throughput of LoRaWAN reaches a state of stability once the number of nodes reaches 2000. Simply put, the LoRaWAN throughput has reached its maximum capacity at this stage. Conversely, the throughput of The suggested protocol demonstrates a distinct rise in bit per second as the number of nodes increases. Therefore, it exhibits enhanced scalability in comparison with LoRaWAN. When the number of nodes, denoted as N, is set to 6000, the throughput of the proposed protocol utilising MBMZ-LoRa is twice as high as the throughput achieved with LoRaWAN.

4.5.4 Energy Consumption

The energy consumption is calculated by dividing the total energy spent by all LoRa nodes by the number of packets successfully received by the network server. The energy usage per successful transfer for both methods is illustrated in Figure 4.13. MBMD-LoRa exhibits a notable reduction in energy use. These findings demonstrate the significant improvements in energy efficiency demonstrated by the proposed MBMD-LoRa algorithms, with both algorithms performing equally. The slim data rate in MBMD allows the LoRa algorithms to achieve optimal spreading factor allocation, resulting in maximum power efficiency. Despite the lack of use of SF12 in the MBMD-LoRa method, both methods nonetheless exhibit equivalent levels of energy consumption due to the extensive usage of SF10 and SF11 in non-B_f. On the other hand, the B_f technique mostly utilises SF7 and SF8, while minimising the usage of SF12 illustrated in Figure 4.7. Compared to the legacy versions of LoRaWAN and BE-LoRa, these methods are more energy efficient. The spreading factor utilisation in each f is compared in Figure 4.11. The increased use of SF when BE-LoRa moves from lower SF to higher SF is an obvious reason for increasing energy consumption, while in LoRaWAN all the nodes are close in spreading factor distribution except a small percentage in SF8. This is due to the random distribution in LoRaWAN and not exploiting all levels between the same spreading

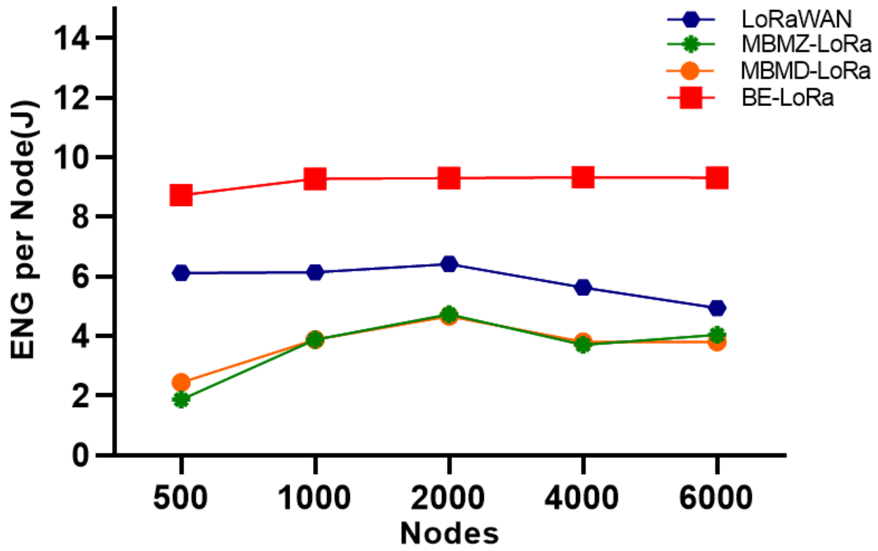


Figure 4.13: Energy consumption

factors, in contrast to the new method which exploits all levels inside the one spreading factor. Therefore, these findings indicate the performance improvements that may be attained by the suggested techniques.

4.6 Discussion

This chapter examines the Multi_Band Multi_Data Rate as a means to achieve scalable communication in long-range IoT networks. The proposed MBMD_LoRa algorithm is a collaboration between the Bandwidth Allocation and Spreading Factor (BASF). Multi-Band is a new direction for LoRa, which enhance LoRa scalability highly. In these algorithms, the LoRa nodes exhibit behaviour that is consistent with the information provided by the network server. This study presents a potentially effective resolution of the issue of LoRa network size, which optimises the number of nodes, packet delivery ratio and energy efficiency. This method has demonstrated that an optimal solution does exist and that it is distinct for every Slim Data Rate. In addition, MBMZ-LoRa has demonstrated efficacy, which is based on MBMD-LoRa and the premise of six zones for all LoRa nodes. The algorithm for MBMD-LoRa enhances the data rate ratio, and a major increase notices in the data rate levels 1 to 6, alongside no changes in DR0. This data rate doubling leads to a decrease in the time-on-air packet size and achieves a greater energy efficiency initially due to the fact that an increase in data rate results in a reduction in $Pckts$ time (ToA). This is in addition to a decrease in collisions caused by $Pckt$ size, which reduces transmission power and retransmission for $Pckt$. The diversity of SF in the cell is the most significant addition because it prevents collisions between nodes, thereby conserving energy by eliminating the need to retransmit $Pckt$. The simulation findings demonstrated that the proposed method provides a superior delivery ratio and reduced energy usage in comparison to BE-LoR and LoRaWAN.

4.7 Chapter Summary

This chapter has presented a novel method MBMD-LoRa and MBMZ-LoRa, to enhance scalability in LoRaWAN protocol as new algorithms alternative to the adaptive data rate. The chapter presents robust processing techniques that have considered the slim data rate characteristics. Analysis of node allocation and moving from one zone to the next zone based on the RSSI signal has also been presented. Finally, this chapter provides a robust analysis of the proposed technique and assesses its generalisation ability and achieves objective two in this thesis. The next chapter presents the second sequential phase to multi-zone multi-data rate with multi-gateways. The next chapter 5 will develop this chapter's idea to enhance the scalability in a multi-gateway scenario without wasting channel availability.

Chapter 5

ZBMG-LoRa Scalable LoRaWAN for Internet of Things: A Zone-based Multi-Gateway Multi-Data Rate Approach

5.1 Introduction

In LoRa technology, packets can be received concurrently by multiple gateways. Subsequently, the network server selects the packet with the highest receiver strength signal indicator (RSSI). However, this method can lead to the exhaustion of channel availability on the gateways. The optimisation of configuration parameters to reduce collisions and enhance network throughput in multi-gateway LoRaWAN remains an unresolved challenge [22]. This chapter introduces a novel low-complexity model for ZBMG-LoRa, which categorises nodes into distinct groups based on their respective gateways. This categorisation allows for the implementation of optimal settings for each node's subzone, thereby facilitating effective communication and addressing the identified issue. By deriving key performance metrics (e.g., network throughput, energy efficiency, and probability of effective delivery) from configuration parameters and network size, communication reliability is maintained. Optimal configurations for transmission power and spreading factor are derived by ZBMG-LoRa for all nodes in LoRaWAN networks with multiple gateways. In comparison to the original LoRaWAN protocol and other related state-of-the-art algorithms, the findings demonstrate that the novel approach achieves a higher packet delivery rate and more energy efficiency.

5.2 Background

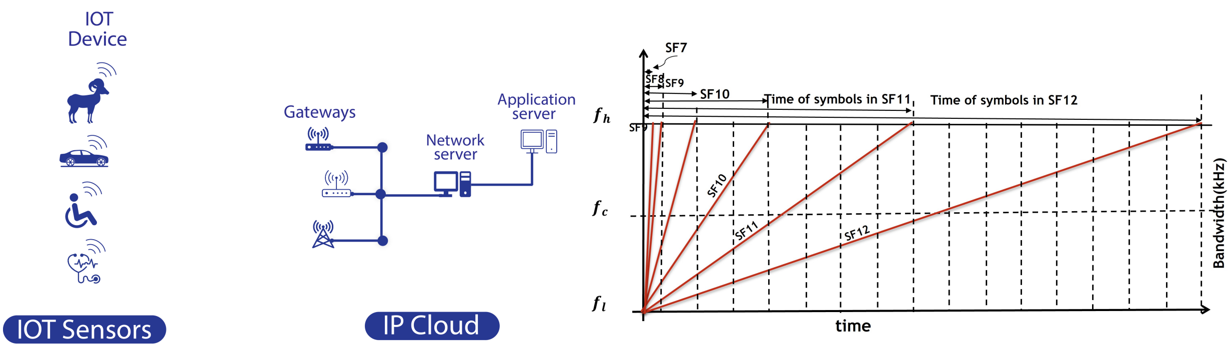
The LoRaWAN architecture is a star topology that comprises nodes, gateways, a network server, and an application server. The nodes send packets to the GWs via uplink communication, and the GWs send them on to the network server [134]. It is important to note that despite the use of joint packet decoding, the throughput performance of LoRaWAN cannot be guaranteed. The rationale is derived from the random access technique used in LoRaWAN [75]. More precisely, in LoRaWAN, the Aloha-type random access mechanism allows each node to decide when to access the channel, which leads to collision and increases the unsuccessful reception rate. The Aloha protocol is renowned for its simplicity and ease of implementation, but it is plagued by poor performance due to the potential for a large number of channel access requests to occur simultaneously [135]. This may result in numerous packet collisions, even when several base stations are working together to receive them. Developing an effective strategy to manage the increasing number of IoT devices and applications supported by LoRaWAN is crucial for the successful implementation of LoRaWAN in large-scale wide-area IoT scenarios with massive machine-type communications (mMTC). The existing literature on multi-cell Aloha networks with individual packet decoding has consistently noted that the configuration parameters, including the channel access probability, have a substantial impact on the throughput performance [136]. Multiple gateways could be a solution in a LoRa network because the packet can be received by numerous gateways, and the network server subsequently selects the packet with the strongest signal [54], thereby improving reliability [137]. Nevertheless, the packet overlaps between multiple gateways when it is sent to more than one simultaneously. Furthermore, this behaviour depletes the availability of channels on gateways. Essentially, a packet can be decoded successfully if it is received by at least one gateway with a perfect setting. Optimal performance in the multi-GW LoRaWAN with joint packet decoding requires proper configuration parameters. Nevertheless, the ideal adjustment of configuration parameters in LoRaWAN is still uncertain.

This study asserts a two-step algorithm to significantly improve the scalability and reliability of LoRaWAN networks with multiple gateways. Firstly, this method involves thoroughly evaluating all paths between the end device and the gateways in the coverage area. It is essential to assess the link budget and select the path with the lowest path loss to ensure the best path and gateway are chosen, thus guaranteeing a highly reliable connection. Secondly, the study formulates a multi-objective optimization problem to determine the optimal ratio of nodes at each gateway and each SF zone definitively. This is aimed at significantly enhancing the LoRaWAN network throughput while unequivocally minimizing energy consumption. this suggested technique concurrently configures the GWs, SFs, Chs, and TPs for all nodes in LoRaWAN networks with gateways and spreading factor zones compared to the state-of-the-art. Furthermore, it circumvents the use of SF11 and SF12, which are the primary factors contributing to a rise in collisions. In contrast to the several works such as [22] employ SF 11 and SF12. That is why this approach outperforms others in terms of packet delivery ratio, throughput, and overall energy usage. Furthermore, it does not need any synchronisation procedure and may be used for class A with an unverified transmission mode. In this mode, nodes do not seek an acknowledgement from the network server after each transfer. In contrast to the works by authers in [84, 138, 139, 140, 141, 142, 143], this proposed algorithm is compared with ADR and other state-of-the-art algorithms. The results unequivocally demonstrate that this solution significantly enhances the energy efficiency of the network for the same reasons mentioned previously.

5.3 LoRa Multi-Gateways

Extensive research has been conducted on LoRaWAN, beginning with the single-GW scenario. The study in [144] offered empirical findings that demonstrated the impact of several system characteristics, including spreading factor, coding rate, payload size, and packet transmission interval, on the performance of LoRaWAN. The authors of [145] offer decentralised dynamic SF allocation algorithms that use deep reinforcement learning to enhance network throughput and minimise energy usage. Based on stochastic geometry[139] [83] demonstrated that the performance of LoRaWAN decreases dramatically as the amount of nodes increases. This suggests that the network's performance in densely distributed networks is limited by interference among nodes rather than noise. According to the findings in research [146], the packet error rate in LoRaWAN rises as the network load grows. The study also determined the maximum network load that guarantees reliable communication. In a study conducted by Authors in [147], the performance of LoRaWAN was examined, and it was discovered that in order to meet a certain quality of service (QoS) criterion in a LoRaWAN with a single gateway, the number of devices must be restricted. In order to enhance the performance of multi-GW LoRaWAN, [148] and [149] offer SF allocation algorithms for the multi-GW situation. In their study, the authors In [148] introduced a technique called 'spreading factor with priority (SF-P)' to achieve an optimum distribution of nodes in a multi-GW LoRaWAN. This approach aims to enhance the network performance and accommodate various IoT applications while also considering the specific priority needs of each application. In order to improve the PDR in both single-GW and multi-GW LoRaWAN networks as new devices are added, an SF allocation algorithm was suggested in [149]. The allocation strategy relies on the link PDR network throughput and the distribution of Service Factors per gateway in the network. Studies conducted by authors in [150] and [151] utilised simulators to examine the performance of multi-GW LoRaWAN under various conditions. R. Marini et al. [150] provide a detailed analysis of the performance of multi-GW LoRaWAN in the EU868 MHz spectrum and the 2.4 GHz spectrum using a simulator. In dense scenarios with a variable number of gateways and bidirectional network traffic, the performance of adaptive strategies, specifically the "adaptive data rate and adaptive data payload (ADP)" approaches, is compared in [151]. In[152], authors developed an algorithm that can accurately determine the number of gateways that need to be activated based on the downlink traffic demand in a network. This algorithm is particularly useful in situations where the positions of the nodes are not known. The authors of [54] and [153] conducted a study on enhancing the efficiency of multi-GW systems by considering the aspect of diversity.

A novel cooperative decoding scheme was introduced in [54], which utilises GW diversity to enhance decoding reliability. This scheme takes advantage of multiple copies of the same packet received by different gateways. Authors suggested incorporating spatial diversity into a multi-GW LoRaWAN network [153]. This approach assists in reducing the impact of path attenuation and enables successful decoding of weak signals that would otherwise be undetectable. In their publication, researchers [20] introduced a capture-based model that aims to optimise inter-packet error correction codes (ECC) in order to ensure dependable communication. Authors in [90] and [154] employed stochastic geometry methodologies to evaluate the efficiency of multi-GW LoRaWAN. They made the assumption that the spatial distribution of nodes adheres to a Poisson point process. The majority of previous studies aimed at enhancing the performance of LoRaWAN have focused on resource allocation, specifically the spreading factor [145], [149]. Insufficient focus has been given to the Aloha-type random access scheme in LoRaWAN. The existing literature on multi-cell Aloha networks with individual packet decoding has consistently noted that the configuration parameters, including the channel access probability, have a substantial impact on the throughput performance [136]. Optimal performance in the multi-GW LoRaWAN with joint packet decoding requires proper configuration parameters. Nevertheless, the ideal adjustment of configuration parameters in LoRaWAN is still uncertain.



(a) (b)

Figure 5.1: a:LoRa Network Artichture. b: Timing of LoRa spreading factor

The LoRaWAN specification encompasses the upper layer protocols and network architecture necessary for enabling end devices to establish direct connections with gateways. This is achieved via the use of an ALOHA-based multiple access scheme operating within the sub-GHz ISM bands. The gateways are then linked to the NS which carries out crucial network-level operations such as device authentication, downlink transmission scheduling, and the implementation of a portion of the ADR algorithm, amongst others. The LoRaWAN mechanisms adhere to the regional regulations for the use of the sub-GHz ISM band[1]. These regulations include several aspects, including the maximum transmission power and duty cycles. This study postulates the utilisation of LoRaWAN technology inside the European region, where the transmission power and duty cycle are limited to 14 dBm and 1%, respectively, specifically for the default frequency channels. The classification of device classes is determined by the specific application requirements pertaining to both energy efficiency and downlink communication latency. The EDs with the highest energy efficiency, sometimes powered by batteries, are classified as Class A devices. These devices exhibit the greatest delay in receiving downlink messages, which are sent by the network immediately after an uplink transmission. The inclusion of different device classes offers supplementary possibilities for the reception of downlink signals but at the cost of increased energy consumption.

5.3.1 Multi-Gatweay Issues

Gateways receive LoRaWAN packets sent wirelessly from an end device and then send that packet to the network server. In addition, they transmit data packets from the network server back to the device. One important feature of these gateways is their ability to convert the received signals into binary data, which is then stored in a buffer called a packet [155]. This packet is then sent over the gateway's backhaul, which is the gateway's link to the Internet via Ethernet, Wi-Fi, or Cellular connection [156] . The gateways receive messages from an end device, known as an uplink, along with the accompanying information for each uplink. This metadata includes the RSSI, SNR, ToA, frequency channel, and data rate. After receiving an uplink message and its corresponding metadata, the gateway transmits the message to the network server.

An advantage of implementing a LoRaWAN network is the ability to easily include extra gateways in areas where network congestion may occur due to an overload of uplink traffic, which may lead to a shortage of accessible frequencies for transmission. In some circumstances, it could be necessary to include gateways in order to address limitations in the available time-on-air of the gateway or to overcome network coverage issues that prevent reliable reception from end devices. Nevertheless, the extensive communication range of LoRaWAN might result in overlapping coverage areas for gateways. Consequently, packet transmissions from nodes inside these overlapping areas may clash, leading to a decline in network performance. Optimising the configuration parameter values to minimise collision and maximise network performance in multi-gateway LoRaWAN remains an unresolved issue [156, 157]. To address this problem, this study proposed ZBMG-LoRa to make the network adapt to the additional gateways automatically by using a low-complexity model for multi-gateway LoRaWAN. This model categorises nodes into various groups depending on the gateways they can interact with. Adjacent devices to new gateways get automated instructions to transfer data at a greater rate, reducing the time on air and getting directed to transmit at a lower power level. Additionally, this substantially enhances the longevity of the battery in battery-operated devices and enables a greater number of devices to connect to the network. This straightforward method provides a significant benefit compared to conventional mobile networks. Integrating a new base station into a conventional mobile network often requires a complete overhaul of the radio configuration, which involves modifying the frequencies used by all neighbouring base stations.

5.4 System Model for LoRaWAN

The Bit Rate (BR) is important in network systems as it plays a decisive role in determining the pace at which data is transferred. Additionally, it directly impacts network performance, ensuring that application requirements are met. The LoRa network bit rate can be calculated using equation 5.1 [129].

$$R_b = f * \frac{b}{2^f} * cr \quad [bits/s] \tag{5.1}$$

Where f is the spreading factor and b is the channel bandwidth and the cr is the coding rate. The spreading factor in LoRa modulation pertains to the quantity of chips employed for encoding each symbol, and it has a direct impact on both the data rate and communication range. The f

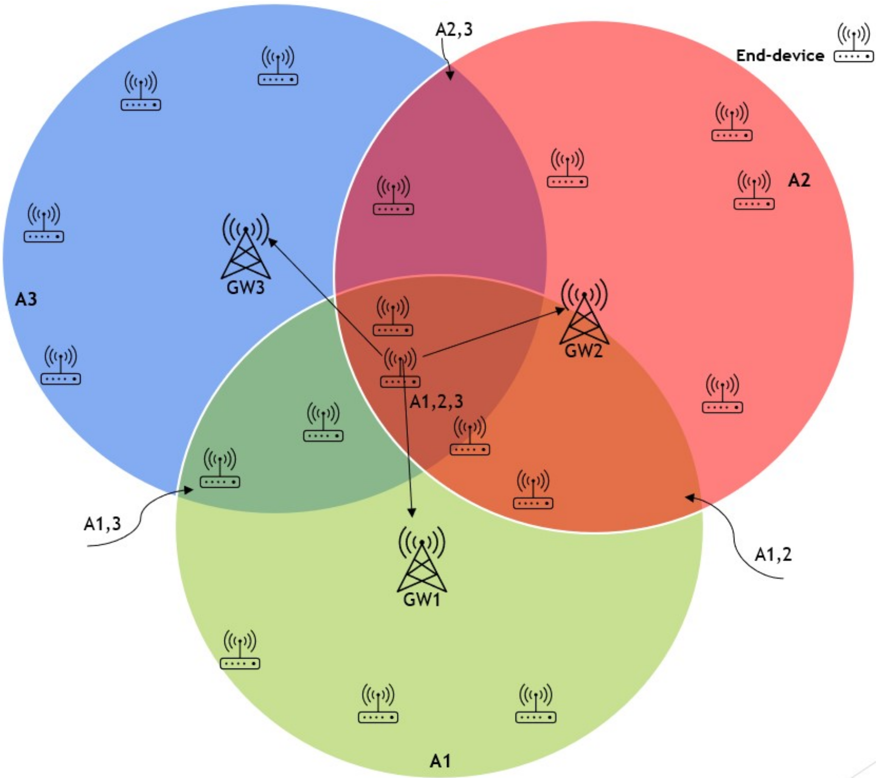


Figure 5.2: Overlapping in LoRa Network deployment multi-gateways

determines the duration of each symbol transmission and the sensitivity to noise. The spectrum of spreading factors in the context of SF7 to SF12 is characterized by a doubling in symbol duration with each incremental increase in the spreading factor, resulting in halving of the data rate. The concept of a high spreading factor refers to the utilization of a larger number of chips in a spread spectrum communication system. A spreading factor with a high value, such as SF12, offers enhanced signal resilience and facilitates long-distance communication. This technology is appropriate for situations that necessitate extensive coverage over great distances, even with the trade-off of reduced data transmission rates. A low spreading factor, exemplified by SF7, is associated with increased data rates but reduced transmission range in comparison to greater spreading factors. Applications that emphasize better data throughput over long-range coverage can benefit from its usefulness. The determination of

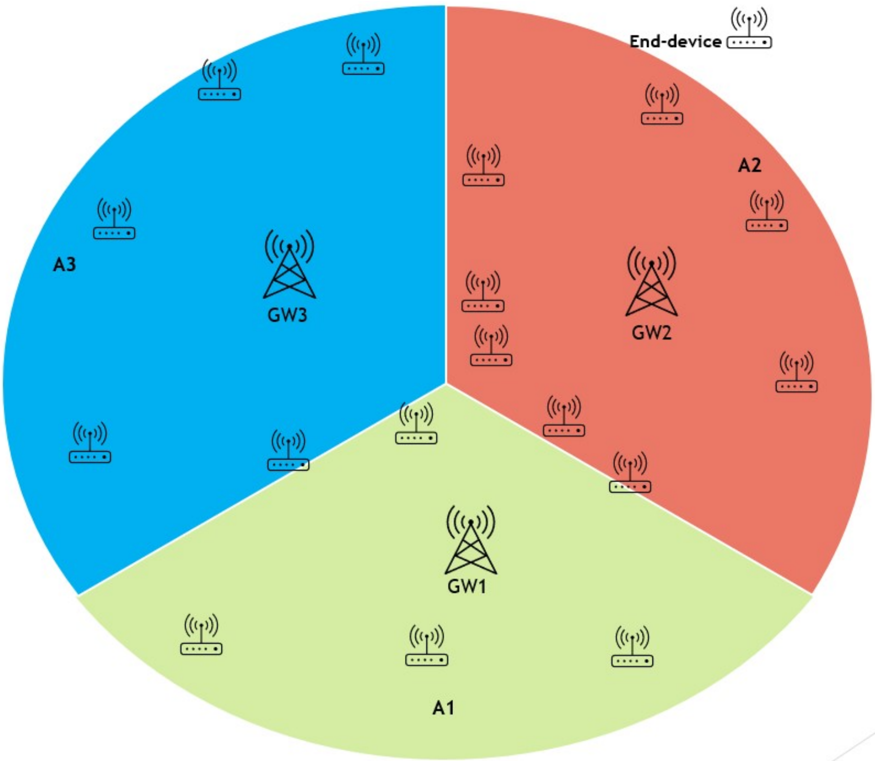


Figure 5.3: No overlapping in the proposed deployment multiple gateways

the suitable spreading factor is contingent upon the particular demands of the application, taking into account several elements like the intended data rate, range, power consumption and susceptibility to interference.

5.4.1 Link and Propagation Model

The link budget of a wireless system or network refers to the comprehensive assessment of the total gains and losses incurred during the transmission process, encompassing the transmitter, propagation channel and the intended receiver. The gains and losses encompass several factors such as system gains and losses related to the antenna, matching networks, and other components, as well as losses linked with the propagation channel itself, which can be determined using either modelling or observed data. In general, when considering channel

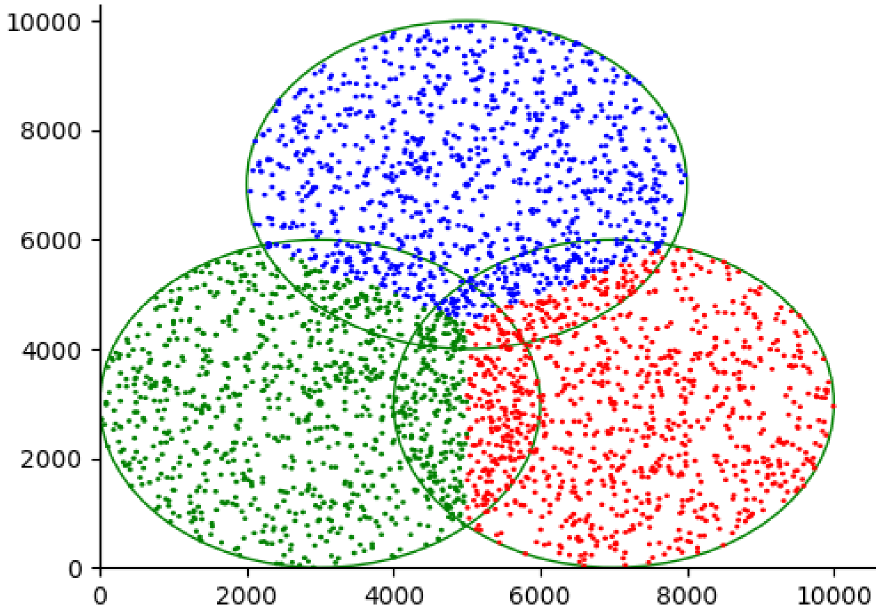


Figure 5.4: No overlapping in ZBMG-LoRa system from the simulator

mechanisms that exhibit random variations, such as multipath and Doppler fading, it is customary to incorporate supplementary margin based on the expected severity. The link budget for a wireless network link can be mathematically represented in equation 5.2 as follows:

$$P_{rx}(dBm) = P_{tx}(dBm) + G(dB) + PL(dB) \tag{5.2}$$

Where P_{rx} is receiving power, the P_{tx} is transmission power, $G(dB)$ is the antenna gain of transmitter and receiver, and the $PL(dB)$ is the path loss. All gain can be written as equation 5.3:

$$G(dB) = G_{tx}(dB) + G_{rx}(dB) \tag{5.3}$$

while the all-path loss is represented in equation 5.4:

$$PL_{Total}(dB) = PL_{Env} + PL_{tx}(dB) + PL_{rx}(db) - X_{\sigma} \tag{5.4}$$

With $G_{tx}(dB)$ minus $PL_{tx}(dB)$ and $G_{rx}(dB)$ minus $PL_{rx}(dB)$ set to zero,

X_σ is the fading margin while $PL_{Env}(dB)$ is dictated by the communication environment.

The popular log-distance path loss model [130] is employed to model the deployments in heavily populated areas. This architecture has been chosen because it suits LoRa deployment scenarios. This model describes path loss as a function of communication distance d as in equation 5.5:

$$PL_{Env}(d) = PL_{Env}(d_0) + 10_\lambda log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{5.5}$$

$PL_{Env}(d)$ represents the path loss in dB, $PL_{Env}(d_0)$ signifies the average path loss at the intial distance $d0$, λ denotes the path loss exponent and X_σ $N(0, \sigma^2)$ represents the normal distribution adjusted for shadowing with a mean and a variance of zero. Additionally, the simulations conducted using the settings documented by Martin Bor[131], Mariusz Slabicki[80] and [132] demonstrated comparable outcomes in relation to scalability. Moreover, a novel channel frequency plan has been conducted in more detail in the next section.

5.4.2 Simulation Model

There are multiple factors that affect whether a receiver can decode one or two packets, or none at all, when two LoRa signals collide. These factors include Carrier Frequency, Spreading Factor, voltage, and duration. The collision between packets p_1 and p_2 happens only when all the conditions defined in equations 5.6 are met:

$$C_{pckt}(p_1, p_2) = \begin{cases} 1 & if \quad (O(p_1, p_2) \wedge C_{fr}(p_1, p_2) \wedge C_f(p_1, p_2) \wedge C_{pw}(p_1, p_2) \wedge C_t(p_1, p_2)) \\ 0 & \text{else} \end{cases} \tag{5.6}$$

The situation in which two transmissions collide on $C_{fr}(p_1, p_2)$ may be defined by considering the centre frequencies of transmission (p_1, p_2), denoted fr_{p_1} andfr_{p_2} respectively. Additionally, the least allowable frequency offset is represented by a threshold. Semtech SX1272 has a minimum acceptable frequency deviation of 60kHz when using a bandwidth of 125kHz, 120kHz when using a bandwidth of 250kHz, and 240kHz when using a bandwidth of 500kHz. The orthogonal Spreading factors $C_f(p_1, p_2)$ are employed in this case. Therefore, it is possible to correctly decode transmissions that have different SF (while maintaining the same CF and BW), provided that there are two accessible receiver pathways. $C_{pw}(p_1, p_2)$ occurs When two signals are present at the receiver, where the stronger signal suppresses the weaker signal. Thus, the received signal intensity may vary by a small degree. However, when the difference is too slight, the receiver switches between the two signals and is unable to decipher either, where the two packets are denoted as (p_1, p_2). The expression $O(p_1, p_2)$ represents the time complexity of a function or algorithm in terms of two variables,(p_1, p_2), when the periods of their reception overlap. In order for the receiver to recognise the preamble and synchronise, it requires five symbols. Eight preamble symbols were included in the broadcasts. Hence, the receiver looks at the weak transmission after three symbols, but the strong transmission suppresses its signal, corrupting the packet. It may be inferred that packets can overlap if, in the event of a weak packet, at least five preamble symbols remain undamaged (i.e. the most important part of a packet's receipt begins with the final five preamble symbols). Figure 2.6 illustrates the packet and the equations 5.7,5.8 and 5.9 show how the time preamble, the symbol time and the number or length preamble are calculated respectively.

$$T_{\text{preamble}}(f) = (L_{\text{preamble}} + 4.25) \cdot T_{\text{symbol}}(f) \tag{5.7}$$

$$T_{\text{symbol}}(f) = \frac{2^f}{b} \tag{5.8}$$

$$\mathrm{L}_{\text{preamble}} = \left(\frac{2^f \times 12.25}{b}\right) + \left\{8 + \max\left(\text{ceil}\left(\frac{8PL - 4f + 28 + 16CRC - 20IH}{4(f - 2DE)}\right)(CR + 4), 0\right)\right\} \tag{5.9}$$

Given the dependencies provided, the variable PL represents the quantity of payload bytes, f and b represent the concepts of the spreading factor and bandwidth, respectively. The value of H is 0 when the header is enabled and 1 when no header exists. When the low data rate optimisation is enabled, the value of DE is 1. Conversely, when the optimisation is removed, the value of DE is 0. The coding rate ranges from 1 to 4. It may be inferred that if there is a need to decrease the duration of airtime, and the length of the packet is predetermined, then the header data can be omitted. The duration of the payload can be calculated by multiplying the symbol period by the total number of payload symbols.

The sensitivity of the gateway and end device receivers for a given spreading factor can be denoted as $S_G(i)$ and $S_e(i)$ in decibels (dB), respectively. According to [72], observation reveals that augmentation of SF results in improved sensitivity, with consistent increments of 2.8 dB, while decreasing BW from wider bandwidth to narrow bandwidth results in improved sensitivity, from 3 to 4 dB. For Downlink (DL) transmissions, the consideration of the sensitivity of an end device is expected to be lower than that of a gateway by introducing a 3 dB offset. Sensitivity values are utilised to ascertain whether a device detects a packet. The sensitivities are represented by equation 5.11 given in [72] [158].

$$S_{(f,b)} = -174 + 10log_{10}b + NF + SNR_f \tag{5.10}$$

$$P_{rx}(n) > S_g \tag{5.11}$$

The first term is a result of thermal noise within a bandwidth of 1 Hz and can only be altered by modifying the temperature of the receiver. The second term, b, refers to the bandwidth of the receiver. NF - the receiver noise figure is a constant value that remains unchanged for a specific hardware implementation. The term SNR_f represents the signal-to-noise ratio that is necessary for the underlying modulation technique as illustrated in Table 2.1. If the power of a signal with a spreading factor f

of node at the receiver's location falls below the thresholdS_g, it cannot be detected by the gateway. Conversely, it can be detected if the received power exceeds the necessary sensitivity. This scenario also presumes that the recipient synchronises with the incoming signal and commences the reception of the packet. This suggests that once a packet is received with sufficient power to initiate detection, it will remain detectable (i.e., over the sensitivity threshold) until it is fully received. If multiple signals with individual powers below the sensitivity threshold arrive simultaneously at the receiving antenna, they cannot be recognised by the receiver, even if their combined power is above the sensitivity threshold and a collision might have happened between packets.

5.5 Zone-based Multi-Gateway system

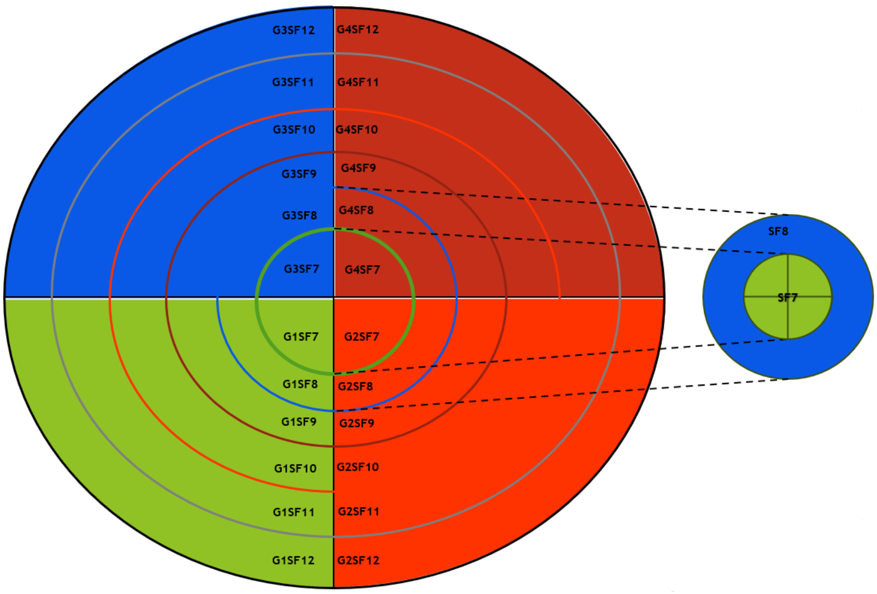


Figure 5.5: ZBMG-LoRa deplyment

5.5.1 ZBMG-LoRa system

ZBMG-LoRa is a zone overlapping resolution strategies assuming that a set of N nodes exists that are random dispersed around gateways with space 1500 m between the gateways across an area of $7000m^2$, with these gateways, each with three main channels. ZBMG-LoRa system has two steps: First, avoid the behaviour of LoRa sending to all gateways when the network infrastructure contains multiple gateways. Although this is an advantage of redundancy in terms of highly guaranteeing packet reception, it leads to high collision and large energy consumption. The optimal setting for the node could guarantee a successful receiving packet. Disabling multicast addressing and enabling unicast addressing should be returned with $Fsetting$ to activate the unicast $DevAddr$ for the node. This noval method aims to quantify the mean likelihood of achieving successful packet reception for each node in every gateway zone in the network.

Accordingly, the proportion of nodes configured with gateway g is given by the following equation.

$$\sum_{g=1}^{G} \alpha_g = 1 \quad \forall g \in GWs \tag{5.12}$$

Where g from 1 to G refers to the maximum number of gateway. The LoRa MAC layer is based on ALOHA MAC protocol that operates without acknowledgements. It is assumed that the nodes transmit packets autonomously, without any dependence on each other or on their geographical locations. The proportion of nodes configured with spreading factor f is given in [74].

$$\sum_{f=7}^{12} \zeta_f = 1 \quad \forall f \in SFs \tag{5.13}$$

Where f ranges from 7 to 12. A packet production at the deployment area of nodes follows a Poisson distribution, with the rate G_f in all zones of gateways and spreading factors $zone_{g,f}$ Figure 5.5 shows the deployment of nodes-based gateways and based spreading factor respectively. Now, let us suppose a node located at a distance di from the gateway, which is transmitting messages μ with a spreading factor of f. Given the assumption of uniform transmission parameters across all nodes, the potential sources of interference can be identified based on the path-loss characteristics of the signal as in equation 5.5. Specifically, all nodes located at a distance of di from the gateway, where maximum distance is defined by the equation 5.14:

$$D = d0 * 10^{\frac{PL_{env}}{10\lambda}} \tag{5.14}$$

where λ represents the path loss exponent, therefore, from assuming a uniform distribution of nodes with spreading factor f, the total number of possible interferers may be calculated. $\alpha_g N \frac{(min(d_i,D)^2}{D^2}$ where D is the range. The probability of successful transmission is $P_s(d)$. Ensuring that no potential interfering nodes initiate a transmission during a vulnerability period of 2Tf is crucial to maintaining a secure and reliable system.

$$P_s(d) = e^{-2T_f \mu \alpha_g N(\frac{(min(d_i,D))^2}{D^2})} \tag{5.15}$$

Considering the phenomenon of the capture effect, the successful transmission of a packet by a node can be determined by two conditions: (a) the absence of any other packet with the same spreading factor overlapping with the current packet within the same receiving time t_f, or (b) the power level at the gateway of any other packet with the same SF surpassing the power level of the current packet by a minimum threshold valuePW_{thld} according to the next equation.

$$C_{pckt}(p_1, p_2) = \begin{cases} 1 & if \quad (O(p_1,p_2) \wedge C_{fr}(p_1,p_2) \wedge C_f(p_1,p_2) \wedge C_{pw}(p_1,p_2) \wedge C_t(p_1,p_2)) \\ 0 & \text{else} \end{cases} \tag{5.16}$$

The data rates probability are derived from equation 5.1. The likelihood of success data rate is derived from the equation introduced in [74].

$$Pc_f = \frac{f}{2^f} / \sum_{i=7}^{12} \frac{i}{2^i} \quad \forall f \in SFs \tag{5.17}$$

However, a significant limitation of equation (5.17) it does not consider amount of gateway g and channels variables, and equation (5.12) it does not consider the SF. In order to accurately predict the success probability of this method, it is important to consider the effect of three crucial factors: gateways, channels and spreading factors. By accounting for the impact of GW, Ch and SF on the probability of success, the novel approach has been optimized for maximum efficiency and capacity. According to equations (5.13) and (5.12), the success probability and throughput Tht are expresses in 5.18 and 5.19 respectively:

$$P_s(d) = e^{-2T_f \mu \zeta_f \alpha_g (N \frac{(min(d_i, D))^2}{D^2})} \tag{5.18}$$

$$Tht = \frac{P_s * P_L * N}{\tau} \tag{5.19}$$

where P_L is the data payload and N is the number of EDs, while the collision probability $P_{g,f}$ expresses by equation 5.20.

$$P_{g,f} = \frac{p_g * f}{\sum_{i \in GWs} i} \quad \forall g \in GWs f \in SFs\& \tag{5.20}$$

Moreover, considering multiple channel frequencies, the final equation of collision probability becomes equation 5.21:

$$P_{f,b,ch} = \frac{p_{g,f} * ch}{\sum_{i \in CHs} i} \forall g \in GWs\& f \in SFs\& ch \in CHs, \tag{5.21}$$

The Figure below illustrates the operations of algorithm 3, which involves the allocation of network nodes according to the proximity of the gateway and the minimum path loss. The following step is to divide that gateway area into tiny zones for each spreading factor. For instance, there are four gateways in the network field. The whole coverage area is divided into zones labelled as G1 through G4. Then, each G area divided into six f zones is delineated according to the spreading factors, as depicted in Figure 5.5. Hence, the total small zone is 24, and all nodes which belong to those zones will be allocated to different channels according to equation (5.21).

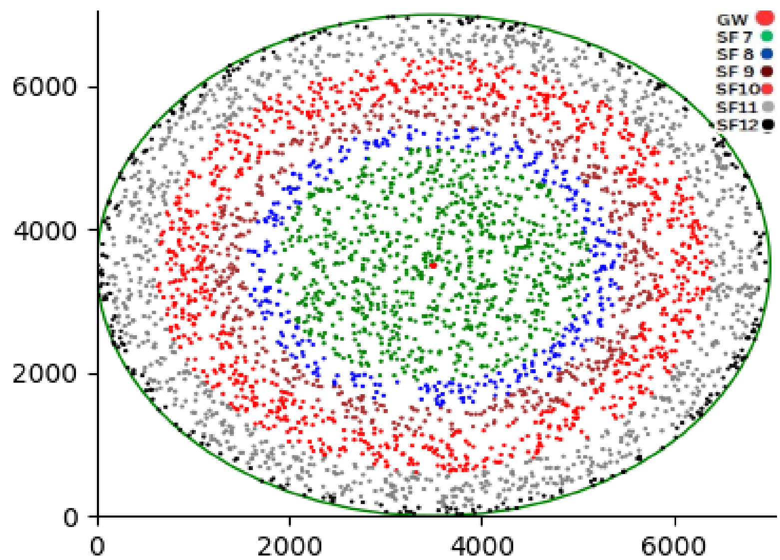


Figure 5.6: ZBMG-LoRa deployment with a single gateway

5.5.2 ZBMG-LoRa Algorithm

The ZBMG-LoRa algorithm is proposed in this section. The initial step in establishing a connection between the nodes and the gateway involves utilising default settings, which entail a high spreading factor, narrow bandwidth and a small code rate. During this connection process, the gateway receives a substantial amount of information from the nodes, including SNR, RSSI, and various other settings, which are transferred to the network server. Firstly, the network server defines transmission power levels as shown in the ZBMG-LoRa Algorithm 1 $P_{tx}level$, SF, GW, and Ch, then lists the settings depending on the number of GWs, as illustrated in Pseudocode row 1. Secondly, the NS sorts the nodes and

Algorithm 3 ZBMG-LoRa Algorithm

Input : n List of N nodes, nGW list of gateways and max dist, base dist.

Output: Ch, TP, SF, BW, CR settings for each i of the N nodesToA_i and k for each zone Processed list.

```
PtxLevel = [ ], SF = [ ], B = [ ], Ch = [ ], Zone = [ ], Se = [ , ] Set[f,B,Cr ,TP, g , ]
/* Assign nodes to best gateway.                                   */
for n ← 0 to N do
    for g ← 0 to nGW do
        /* calc list of PLoss[n, g] based on d[n, g].              */
        append(PLoss[, ])
    end
    PLoss_n[n] = min(PLoss[, ]) n_G = index(min(PLoss[, ])) /* calc RSSI[n] */
    DevAddr = unicast − addressing /* Disable multi-casting and enable
        unicast addressing to assign Node n to Gateway g.          */
end
while i ≤N do
    if RSSI[i] > MinSens then
        for j ← 0 to MDR do
            /* assign parameters setting to set[i] .               */
            if RSSI[i] > Sen[j] then
                if Z_f > ζ_f then
                    SFi ← fj
                    Chi ← Chz
                    ToAi ← ToA(Sj, Bk, CR) Z_f.append([k] + 1)    // count n
                    in each zone.
                else
                    Z_f = Z_f + 1
                    ζ_f = ζ_f + 1
                end
            end
        end
    else
        // Update Node's Transmission power
        TP[i] = TPwLevel[]+ = 1 RSSI[i] = TPwLevel[] − PLoss + GN
        Go to step 6Eng[i]← CalculateEnergy
    end
    TotalEng = Sum(Eng[i])
    i+ = 1
end
return Setting of Each Node and The Average of Energy Consumption and Node's zone
```

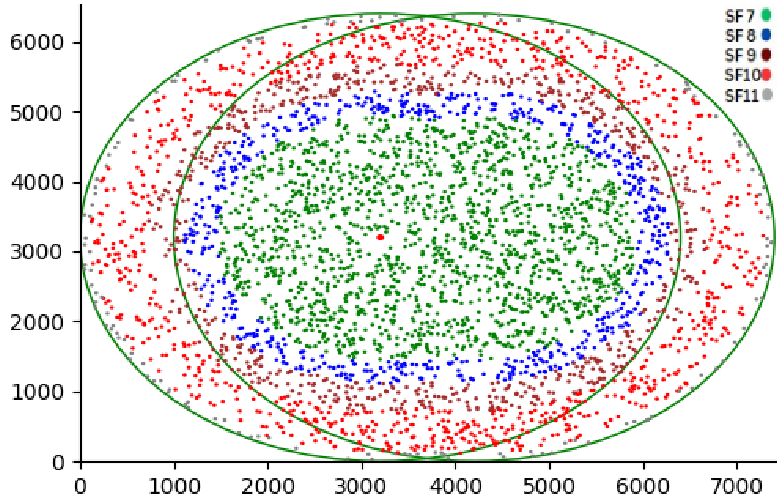


Figure 5.7: ZBMG-LoRa deployment with two gateways

gateway in the matrix depending on PLoss, not d distance. Subsequently, as illustrated from row 3 to row 7, the algorithm proceeds to evaluate the connection and link budget by comparing the nodes' RSSI values to the gateway's sensitivity. Based on the node's link budget and its RSSI, the best setting is selected from multiple configurations $Set[SF, GW, TP, CH]$, which returns the best gateway for a reliable connection. The main objective is to select the optimal setting that ensures a reliable connection while minimising power consumption.

In this algorithm, the selection of node configuration is not solely based on spreading factor and transmission Power as in conventional methods. Instead, the multi-data rate is incorporated, which takes into account both the multi-gateway, spreading factor and multi-channel, in addition to the slim TP steps. The ZBMG-LoRa algorithm is designed based on the previous work MBMD-LoRa to determine the optimal route and rank for a novel technique, with the objective of establishing a reliable and efficient connection. The network server initiates the assessment of the RSSI of nodes and compares it with gateway sensitivity, then assigns them the configuration that aligns with the specific circumstances of each node and

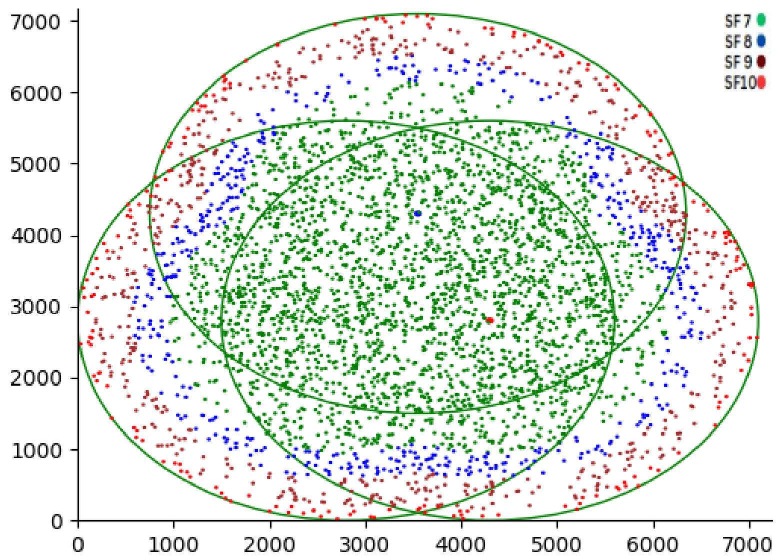


Figure 5.8: ZBMG-LoRa deployment with three gateways

assigns that node to the proposed gateway by increasing the value of k in zone ζ_f. If the node's RSSI is not more than the gateway sensitivity, the algorithm increases the transmission power of that node as in rows 25 to 29, then reassesses the node's link budget occurs as in row 6 to obtain the suitable setting set_i for the node, and so on. The use of diverse transmission characteristics, such as spreading factors and gateways, leads to different settings zones and more available channels. As a result, the disparity in airtime allocation results in differing collision probabilities, hence creating an unfair distribution of resources among nodes inside a certain zone. The ZBMG-LoRa algorithm is proposed using ζf and αg to ensure fair distribution and enhance the packet delivery ratio based on ζ, which is the result of multiplication of equations (5.13) and (5.12), and presents the number of settings. As noted, the algorithm is checking if the number of nodes in Zone Z_f assigned to spreading factor$f$ is not more than the ζ_f value. Otherwise, a move to fulfil the next zone Z_{f+1} is made, and so on, based on the following equations:

$$\sum_{i=7}^{12} Zone_f = 1 \quad \forall f \in SFs \tag{5.22}$$

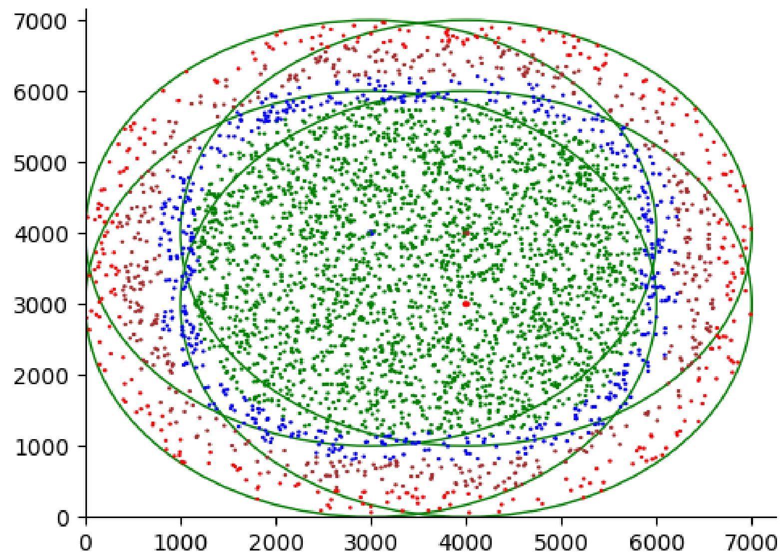


Figure 5.9: ZBMG-LoRa deployment with three gateways

$$\sum_{j=1}^{G} \alpha_g \sum_{i=7}^{12} \zeta_f = 1 \quad \forall f \in SFs, \forall g \in GWs \tag{5.23}$$

ZBMG-LoRa aims to improve LoRaWAN, where the packet reception doubling is not intended to reduce the packet transmission time, leading to fewer collisions and less transmission power. On the other hand, the degree of diversity in SF within a single cell significantly influences the ability of *Pckts* to avoid collisions. ZBMG-LoRa achieves greater energy efficiency initially because an increase in data rate results in a reduction in *Pckts* time, in addition to a decrease in collisions caused by *Pckt* size, which reduces transmission power and retransmission for *Pckt*.

5.6 Discussion and Performance Evaluation

The effectiveness of this proposed resource allocation solution, which is based on the multi-band multi-data rate ZBMG-LoRa algorithm, is illustrated in this section. The evaluation was conducted by LoRaSim, a discrete-event simulator developed by Bor et al.[131]. The simulator uses the Simpy library to analyse scalability and collision issues in LoRa networks. Python 3.9 is utilized to construct the simulations. The distinct approaches have been created that mainly vary in the allocation of SFs, where specifically the ZBMG-LoRa-LoRa is gateway-based allocation with α_g six distributed zones ζ_f. Given that these approaches are designed for large-scale dense networks, the simulations were conducted with a substantial number of nodes, ranging from 500 to 4000. These nodes were randomly dispersed throughout an 7 km^2 geographical area. In addition, this study assumed the presence of a LoRa network with multi-gateways positioned at the centre of the region with a constant distance between them. In terms of packet size, each node produces packets that are 40 bytes in size. The duration between the arrival of consecutive packets follows an exponential distribution with a mean of 200 seconds. According to [81], the European regional specifications for the LoRa physical layer are employed, with a 1% duty cycle for both the LoRa nodes and the gateway. Table 5.1 presents a summary of the simulation parameters that were utilised. An analysis and comparison of the effectiveness of this approach with state-of-the-art methods in LoRaWAN have been conducted. This evaluation assesses collision probability, throughput, packet delivery ratio and power consumption.

The proposed methodology, referred to as the ZBMG-LoRa framework, aims to optimise and improve the performance of LoRaWAN technology. From Figure 5.7, the zone of spreading factor 7 became wider and wider in Figure 5.8 due to the distance between the gateways. SF 7 has the shortest time on air and the highest data rate, and it is also the most power efficient. On the other hand, the absence of spreading factors 11 and 12 enhances the fairness between the nodes. The proposed methodology achieves higher energy efficiency. This can be attributed to two main factors. Firstly, the increase in data rate results in a decrease in the time required for packet transmission (ToA). Secondly, the reduced collision occurrence owing to packet size leads to lower transmission power and fewer packet retransmissions. Moreover, the inclusion of diverse channels within the cellular network. This incorporation serves the

Table 5.1: Simulation parameters Values

Parameter	Value	Comments
N	500 - 4000	Network Size
GW	1 to 4	Gateways
f	7 to 12	Spreading factors
d_0	1000 m	initial distance
λ	2.32 dBm	PLoss exponent
$PL_{Env}(d_0)$	128.95	Ploss of initial distance
$TPLevel$	2 dBm to 14 dBm	Transmission Power
cr	4/5	Coding Rate
b	[125]kHz	Bandwidth
Area	10000 m^2	Field Area
CF	[860, 864, 868]	Carrier Frequency(MHz)
T(s)	One day	Simulation time
τ	10 min	Round time

purpose of preventing node collisions, hence leading to energy conservation by eliminating the need for packet retransmission.

The algorithm underwent evaluation through comparison with both the standard solution in the field and an alternative approach described in previous literature [131][159]. This evaluation employs an integrated methodology that encompasses both simulations and tests with two scenarios. The first study examines the impact of increasing the number of gateways on this approach, while the second compares this approach to traditional studies in different performance metrics such as packet deliver ratio, collisions, throughput network and energy consumption.

5.6.1 Packet Deliver Rate (PDR)

The Packet Delivery Ratio is defined as the quotient of the total number of received packets higher than the gateway sensitivity. According to Figure 5.10, the PDR of the ZBMG-LoRa scenario in the proposed approach is much higher than the PDR of "Joint throughput-energy optimization in multi-gateway LoRaWAN networks" JTEOMG [22] and LoRaWAN. More

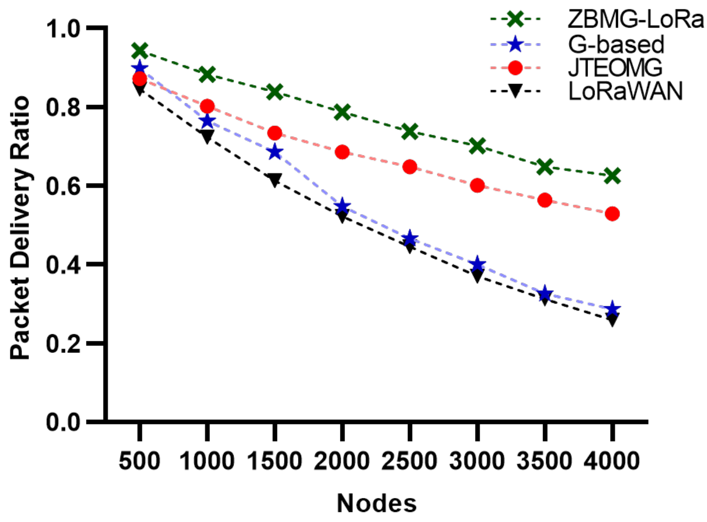


Figure 5.10: PDR of ZBMG-LoRa

precisely, the PDR of this approach is three times higher than the PDR of LoRaWAN when there are 4000 nodes. A multi-gateway scenario provides lower spreading factors to nodes that are close to the gateways to exploit its higher data rate and short ToA of packets, which is why it achieved high PDR as illustrated in Figure 5.11. There is a significant improvement when using two or three gateways compared to using just one. The difference is minimal with these gateways, indicating that three gateways can provide effective convergence in the area.

5.6.2 Throughput

Figure 5.12 illustrates the network throughput as a variable dependent on the number of EDs. The performance in this instance is a direct result of the conduct of the PDR. For small values of Nodes, the Tht grows proportionally with it, as indicated by equation (19). This leads to a high PDR. However, when the number of Nodes becomes excessively big, the PDR starts to decrease significantly, causing a saturation effect on the

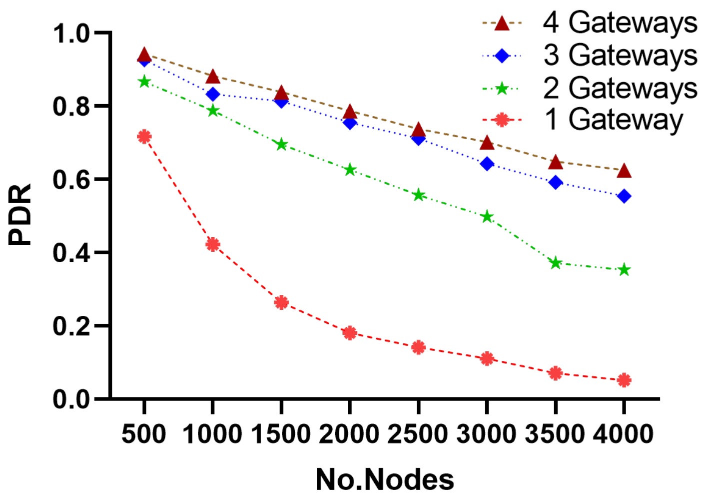


Figure 5.11: Packet delivery ratio with single and multiple gateways

Throughput. Hence, the enhancement of the suggested solutions in comparison to the conventional one is amplified by augmenting the quantity of EDs.To begin with, it is important to note that ZBMG-LoRa iterations of this protocol attain superior data transfer rates compared to LoRaWAN. Furthermore, it should be observed throughput of LoRaWAN reaches a state of stability once the number of nodes reaches 2000. Conversely, the throughput of this suggested protocol demonstrates a distinct rise in bit per second as the number of nodes increases. Therefore, this approach exhibits enhanced scalability compared to LoRaWAN. When the number of nodes is set to 4000, the throughput of this proposed protocol utilising ZBMD-LoRa is more than twice as high as the throughput achieved with LoRaWAN.

5.6.3 Energy Consumption

According to 5.14 clearly presents the total energy usage per T period for each scenario. The energy consumption is accurately calculated using the total energy expended by all LoRa nodes and the number of packets sent. ZBMG-LoRa exhibits a notable reduction in energy use. These findings

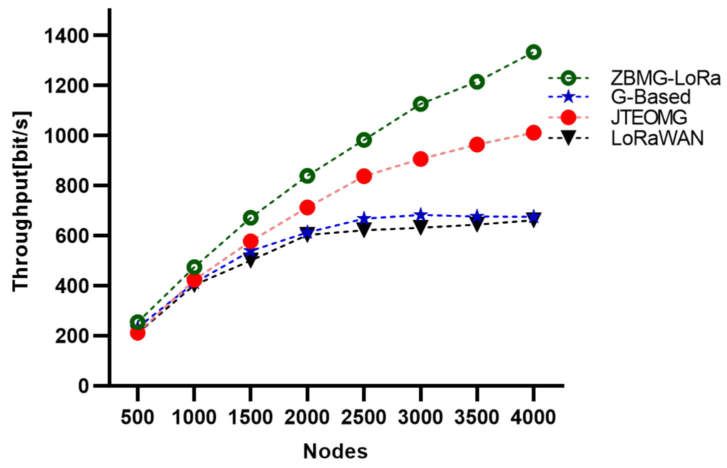


Figure 5.12: Throughput as a function of nodes

demonstrate the significant improvements in energy efficiency demonstrated by the proposed MBMD-LoRa algorithm performance. The energy-saving technique involves using SF7, SF8, and SF9 extensively, with minimal use of SF10, and completely avoiding SF11 and SF12 in the ZBMG-LoRa method. In contrast to the legacy versions of LoRaWAN and JTEOMG, which use all SF levels, ZBMG-LoRa is more energy efficient. The spreading factor utilisation in each f is illustrated in Figure 5.13. The random distribution in LoRaWAN fails to exploit all levels between the same SFs, unlike this approach, which effectively utilizes all levels within a single SF.

5.7 Chapter Summary

This chapter has presented a novel approach to avoid overlapping and enhance scalability in multi-gateways LoRaWAN networks. Robust processing techniques that have considered the increasing gateway to the network and how to avoid high-power-consuming settings to the LoRa nodes were also laid out in this study. An analysis of node allocation with multi-gateways has been presented. This chapter examined the Zone-based Multi-Gateway as a means to achieve scalable communication

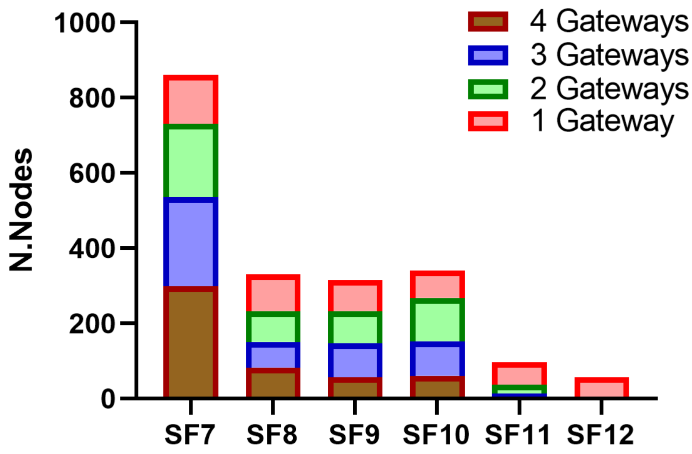


Figure 5.13: Spreading Factor distribution

in long-range IoT networks. The proposed ZBMG-LoRa algorithm is a collaboration between the gateways allocation and spreading factor. The algorithm for ZBMG-LoRa has enhanced the data rate ratio by avoiding using SF 11, 12; this led to a decrease in the transmission time of the packet and achieved a greater energy efficiency initially due to the fact that an increase in data rate results in a reduction in *Pckts* time (ToA). This is in addition to a decrease in collisions caused by *Pckt* size, which reduces transmission power and retransmission for *Pckt*. The diversity of channels in the cell is the most significant addition because it prevents collisions between nodes, thereby conserving energy by eliminating the need to retransmit *Pckt*. The simulation findings demonstrated that the proposed approach provides a superior packet delivery ratio and reduced energy usage compared to JTEOMG and LoRaWAN. A substantial number of nodes in the overlapping coverage area must optimise their settings to maximise network throughput, clearly indicating the trade-off between fairness and efficiency. The issue of fairness warrants significant attention in this future work. Finally, this chapter comprehensively analyses and compares the proposed technique to the state-of-the-art and original protocols. The next chapter presents the fairness between the nodes to guarantee a long lifespan for the LoRa network. The next

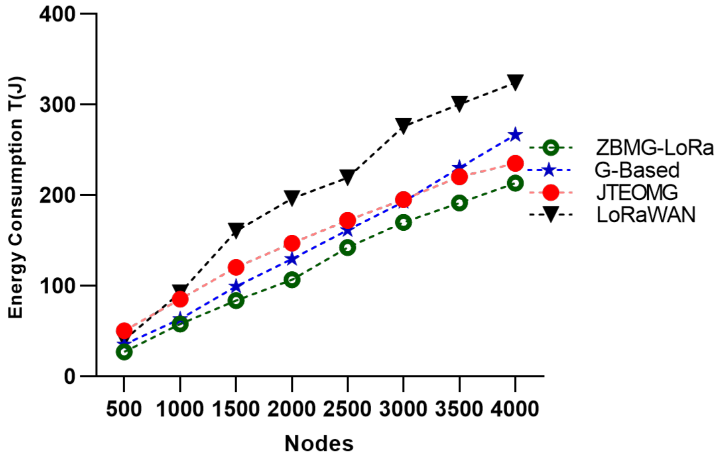


Figure 5.14: Energy Consumption of ZBMG-LoRa

chapter 6 will introduce a new technique to enhance the LoRaWAN network lifespan by designing a fair frame based on a fair time slot to obtain fair energy consumption.

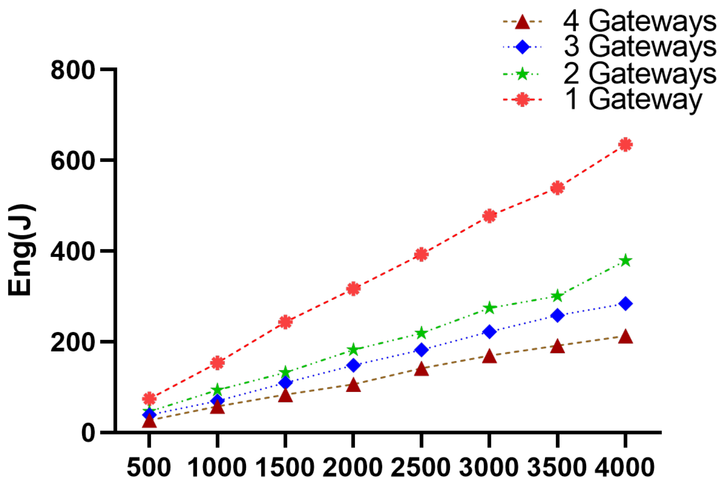


Figure 5.15: Energy consumption with single and multiple gateways

Chapter 6

A Novel Fair Frame Time Slot LoRaWAN Internet of Things

6.1 Introduction

LoRaWAN is especially appropriate for data-gathering applications, such as monitoring, where the longevity of devices and networks is a critical performance metric. In spite of this, LoRaWAN has a scaling difficulty when it comes to supporting hundreds of devices [3]. This challenge arises from the increased collision risk that is inherent in its ALOHA-based physical layer. The performance deteriorates further when some devices consume energy sooner than others, owing to the disparate allocation of spreading factors, hence reducing the network's lifetime. This chapter presents a novel fair frame scheduling method for allocating service functions to nodes in six parallel frames distributed timely on eight frequency band channels with the objective of minimising total data collection time while adhering to radio duty cycle constraints. The result shows that FF-LoRa minimises the time of maximum frame (time a round) to approximately 25%, which makes the farthest device more power efficient and leads to enhancement of the network lifespan. Furthermore, the optimisation of data collection time achieved through FF-LoRa significantly enhances the applicability of LoRa technology for various use cases that require brief data collection intervals. This is particularly pertinent for certain Industrial Internet of Things (IIoT) applications.

6.2 Background

LoRaWAN offers a deploy-and-forget wireless sensing model, and the high link budgets associated with its LoRa modulation render it especially suitable for large-scale data collection applications, including environmental monitoring. As an example, using a normal LoRaWAN setup with a spreading factor of 12 and a bandwidth of 125 kHz, the data delivery rate drops below 50% for gateways that are responsible for supporting more than nine hundred devices [131]. Even in terms of the device's lifespan, recent research [160] reveal that it performs less than predicted. The increase in network traffic results from additional packets required for retransmissions, which in turn leads to a higher incidence of collisions. This escalation in collisions contributes to greater energy consumption and diminishes device lifespan, all without enhancing the packet delivery ratio [160]. LoRaWAN gateways may decode up to 8 concurrent broadcasts if they utilise distinct channels and/or spreading factors, although interspreading factor interference may occur owing to LoRa's poor orthogonality [13].

Furthermore, authors use a celebration between Time Division Multiple Access (TDMA) and ADR, such as "Scalable LoRaWAN Downlink Applications Using an Adaptive Beacon Period Configurator System" [161]. These unique qualities make scheduling and synchronisation difficult, which have not been addressed in time-coordinated networks [162]. A previously published work titled "A Comprehensive Comparison in Time-Slotted Frame between Multiple Protocols in LoRaWAN" [16] finds that LoRaWAN batch data transfer has not been documented as satisfactory in the literature despite its feasibility. It is evident that reliably collecting data over extended periods from a medium to a large number of battery-powered end devices in LoRaWAN remains a significant challenge. For unlicensed networks without a listen-before-talk strategy, regulatory duty-cycle constraints limit LoRaWAN transmissions [1]. In addition, LoRaWAN encounters a significant collision probability attributable to its Aloha-based MAC protocol. This leads to an elevated packet loss rate, impacting network reliability and scalability [131]. This chapter introduces an alternative method for data collection in LoRaWAN. The proposed method is Fair Frame LoRa scheduling named (FF-LoRa) for trustworthy and energy-efficient data collecting through planning transmission allocation that avoids collisions and decreases the collection time interval (time a round). FF-LoRa substitutes the conventional simple random access mechanism employed by LoRaWAN with a coordinated medium access strategy. Network devices are synchronised, and transmissions are planned. While coordinated access has been previously examined in the broader context of wireless networks, this proposal introduces a novel perspective owing to the distinctive attributes of LoRaWAN.

The scheduling algorithm in FF-LoRa operates centrally at the gateway, utilising information gathered from end devices, such as the quantity of end devices and the specific path loss for each device. The schedule optimises throughput by assigning spreading factors, bandwidth, channels, and transmission powers to devices, enabling successful decoding of concurrent transmissions at the gateway. The schedule design incorporates six parallel frames, each corresponding to a specific spreading factor, with certain frames employing multiple channels. The allocation of channels and transmission powers is designed to minimise the effects of imperfect spreading factor orthogonality. The scheduling algorithm operates in a greedy online manner, aiming to minimise data collection time and energy consumption while adhering to duty-cycle regulations. Synchronisation is essential for the effective execution of the schedule; several steps occur previously; the initial step facilitates join requests, join acceptance, and scheduling, while the subsequent stage is designated for synchronisation. FF-LoRa facilitates confirmable (acknowledged) uplink data transmission, while the latter employs a compressed group acknowledgement method to address the duty-cycle constraints at the gateway. The Extensive simulation results show that the Fair frame equalises Frame size in most of the spreading factors, decreasing the network data gathering time during planned transmissions at appropriate periods rather than delivering data immediately upon production. Furthermore, this method increases device lifespan by fourfold to over nine years and provides a data delivery ratio (DDR) of over 96%. The additional purpose of this chapter is to emphasise and highlight key LoRa technological characteristics that must be addressed when designing a Time Slot Frame (TSF), report on existing TSL implementations, and discuss their problems and prospects. The contributions in this chapter are summarised below:

- A novel design fair frame effectively reduces the maximum frame time to approximately 25%. This enhancement promotes greater power efficiency for the most distant devices, thereby extending the overall lifespan of the network.
- This approach demonstrates a greater than fourfold increase in device lifetime, surpassing nine years, and achieves a data delivery ratio (DDR) exceeding 96%.
- The optimization of data collection time achieved through FF-LoRa significantly enhances the applicability of LoRa technology for various use cases that require brief data collection intervals. This is particularly pertinent for certain Industrial Internet of Things (IIoT) applications.
- Summary of the challenges and considerations that should be taken into account when designing a time slot frame.

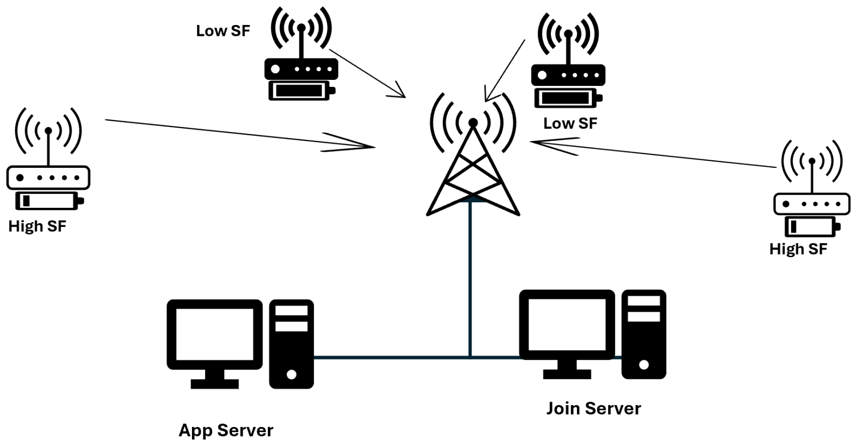


Figure 6.1: The structure of LoRa network

6.2.1 Related Works

TDMA protocols allow several nodes to communicate on the same frequency in distinct time slots, sharing the same transmission channel without collisions. However, there is no synchronisation technique. An approach called on-demand TDMA that uses low-energy wake-up radios and supports both unicast and broadcast modes for triggering nodes and allocating time slots, respectively proposed by Piyare et al. [65]. Gu et al.[100] devised a TDMA-based LoRa multi-channel transmission control with an urgent ALOHA channel and negative acknowledgement (ACK) for wireless sensor networks' one-hop out-of-band control layer. The most important issue for TDMA MAC research is time slot scheduling and allocation. To schedule transmissions, Haxhibeqiri et al. [66] depend heavily on network synchronisation and scheduling entity (NSSE) as the LoRaWAN network's core scheduler.

In particular, the node transmits a request including the traffic periodicity to the NSSE and receives a response regarding the assigned time slots encoded in a probabilistic space-deficient data frame structure. However, given a certain chance, many nodes may occupy the same slot, resulting in collisions. Abdelfadeel et al. [3] presented the FREE system for

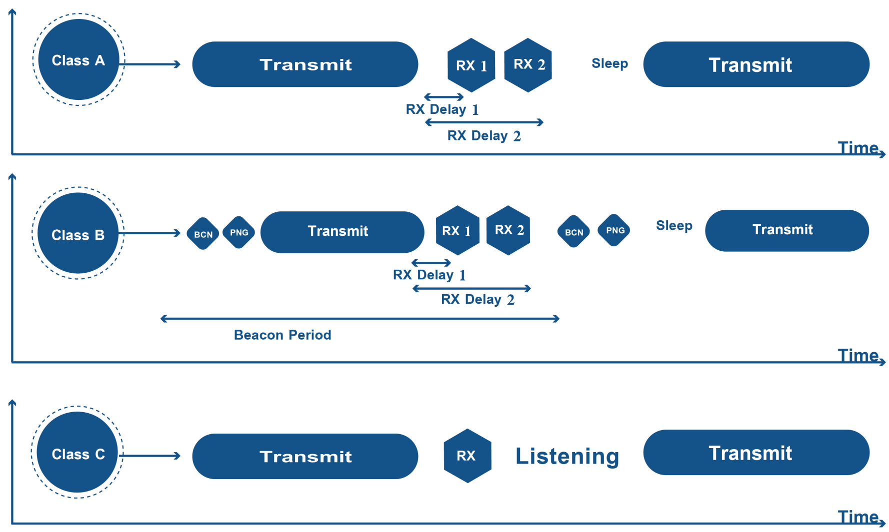


Figure 6.2: The operation modes of LoRaWAN network

fine-grained scheduling. Nodes are specifically allocated transmission parameters including SF, TP, and time slot, and then execute bulk data transfer in the preset time slot. However, while FREE eliminates the collision issue, it does not support real-time transmission. In order to facilitate real-time low transmission, Leonardi et al. [67] suggested.

RT-LoRa,a revolutionary LoRa MAC protocol that can replace LoRaWAN. When using RT-LoRa, the duration of a time slot is constrained by the smallest possible packet size and changes among SFs. Zorbas et al.[23]presented TS-LoRa, an auto time-slotted communication system based on creating hash functions mapping the nodes' provided addresses into unique slot numbers so as to eliminate the need for the centralised scheduler to supply unique time slots for all nodes. In addition, floating nodes suffer more significant losses in signal strength and packet errors as a result of their dynamic attitude as compared to those mounted statically on the ground. This is because the polarisation and directivity of the antenna are affected by the orientation of the antenna. Consequently, Wang et al. [68] suggested a channel access approach called PolarTracker, which makes use of the node's attitude alignment status to plan broadcasts during best-aligned times for higher connection quality. In recent years, numerous MAC protocols have been proposed. These protocols can be broken down into two distinct categories, namely, those that are contention-based [73] and those that are schedule-based [3]. Contention-based media access control protocols are primarily random access protocols, including Slotted-ALOHA and Carrier Sense Multiple Access (CSMA), in which all nodes keep listening to the shared medium and compete for it in order to transmit data. Multiple nodes gain access to a collision-free medium that is partitioned according to time (TDMA) or frequency in the schedule-based protocols. This medium is predetermined(FDMA). Second, Slotted-ALOHA is an offshoot of ALOHA that relies on the relative synchronisation of nodes to bring about interference reduction and peak channel capacity. Time is typically divided into a number of identical time slices, with all nodes gaining access to the channel simultaneously at the start of each slice; if a conflict arises, the transmission must be delayed until the start of the next slice.

In LoRaWAN Time Slot [23], the passage of time is broken up into a series of repeated frames, and each frame is made up of a number of timeslots. In most cases, the size of a time slot is predetermined and is dependent on the chosen payload size, as well as the characteristics of the radio. Multiple users are able to share the same radio frequency in this manner without the risk of causing interference to one another by being assigned to different time slots. The allocation of time slots is an essential step in the execution of every time-division protocol, and it is typically the responsibility of a centralised coordinator (e.g., in cellular networks). In spite of the fact that TDMA communications have been studied for decades and are relied upon by many real-world applications, the design of new Time-Slotted LoRa is still a big challenging problem due to the unique characteristics of LoRa radios and the duty cycle restrictions in sub-GHz ISM bands. The proposed method a fair frame scheduling and synchronization utilise from previous work MBMD-LoRa[158] and LoRadar[163, 164] in terms of optimal sitting for transmission parameters and channel access deduction (CAD). The simulation results show that

FF-LoRa minimizes the time of maximum frame (time a round) to approximately 25%, which makes the farthest device more power efficient and leads to enhancement of the network lifespan.

6.3 Challenges and Considerations For Design

This chapter examines the factors to be taken into account and the difficulties to overcome whilst creating LoRa network protocols for time-slotted medium access. Section 3.5 has discussed a number of different time-slotted solutions that have been proposed in the published research available. Particular emphasis has been placed on open-source protocols that have been put into practice and have been subject to experimental testing.

6.3.1 Multi-gateways, Mobility and Roaming

In LoRaWAN, many gateways may receive communication. In such a scenario, a global synchronization mechanism across gateways may be necessary to ensure that these broadcasts do not interfere with nodes registered in a separate gateway. For instance, gates that overlap may share some spaces. Additionally, nodes may move between several gateways. This requires creating roaming technologies that allow for seamless movement between various service regions. In such a scenario, the frame size must be dynamically modified to accommodate changes in topology. To expand coverage, it would be interesting to examine how multi-gateway deployments may be implemented in a time-slotted context. If the node moves to a different location, its setting will be reevaluated to obtain a new setting that is suitable for that new location. Thus, a new location means a new setting, a new frame and a new slot..

6.3.2 Capacity

In principle, time-slotted networks are only capable of handling a certain number of connections at any one time. Because of the limits placed on the duty cycle, the data transmission periodicity in LoRa networks may be quite infrequent. This essentially implies that a LoRa-based system would not be able to serve certain applications since they demand frequent packet production. A time-slotted system's frame must have a predetermined maximum number of slots in order to accommodate the periodicity of the data it processes. Because of LoRa's very low data rate, as well as the constraints placed on its duty cycle, the network capacity may be severely limited. However, constructing a time-slotted LoRa system in a way that allows it to support a large number of applications is one of the system's design requirements.

6.3.3 Time of Propagation

The LoRa protocol is a type of long-range radio technology that has the potential to achieve a range of several kilometres. Correspondingly, the amount of time required for the signal to propagate might not be considered insignificant. If the design does not take into account this additional time, then there may be problems with desynchronization. This is because signals travel at the speed of light. Therefore, the propagation time may approach 30 microseconds for nodes that are further apart[112]. Incorporating a maximum propagation time into the guard times is a simple approach that may be taken to resolve this issue. This approach reduces the complexity of the programming tasks, has a delay that is low in comparison to the amount of time it takes for data to be transmitted, does not call for the sending of any additional packets (unlike cellular networks), and displays negligible delay.

6.3.4 Battery Lifetime

Due to the additional expense of synchronisation, battery life is a critical concern for all time-slotted solutions. This is because receiving the synchronisation message requires the node to have its radio turned on at regular intervals. The evident correlation between packet length and energy efficiency is broken. It is preferable therefore to provide as little data as possible so that the fewest feasible bytes are actually transferred. In LoRaWAN Class B, for instance, clients may employ the beacon periodicity to synchronise their timekeeping rather than relying on timestamps sent by the network [105]. In addition, when it comes to acknowledgements, the data must be encoded effectively to allow for a low decoding computation cost coupled with short payloads if several acknowledgements are merged into a single packet as was previously described. However, modelling studies have shown that the energy cost of re-transmissions in an Aloha-based system may be larger than the synchronisation cost in high-traffic circumstances[23]. Due to (i) the duty cycle limits and (ii) the need to achieve the lowest feasible wake-up durations, it is important that synchronisation methods be as lightweight and short as possible in the design of a TSL system.

6.3.5 Security

Given that LoRa is vulnerable to a number of vulnerabilities, security and privacy are of primary importance as LoRa network growth accelerates. LoRa's physical layer (PHY) features have exposed novel and potent threats that are difficult to defend, and the protocol's high power efficiency requirement makes developing effective defences much more difficult. Even though the PHY layer security methods can theoretically ensure total security, the lack of robust attributes severely restricts their usefulness. For instance, the majority of current key generation methods only permit the occurrence of two legal parties over a long period of probing, as opposed to group ones. It is difficult for Radio-frequency fingerprint identification (RFFI) approaches to account for immediate features that can be used to discriminate between devices and to ensure that freshly joined genuine devices are compatible with the network. Which leads to some issu such as frame hijacking or slot denial.

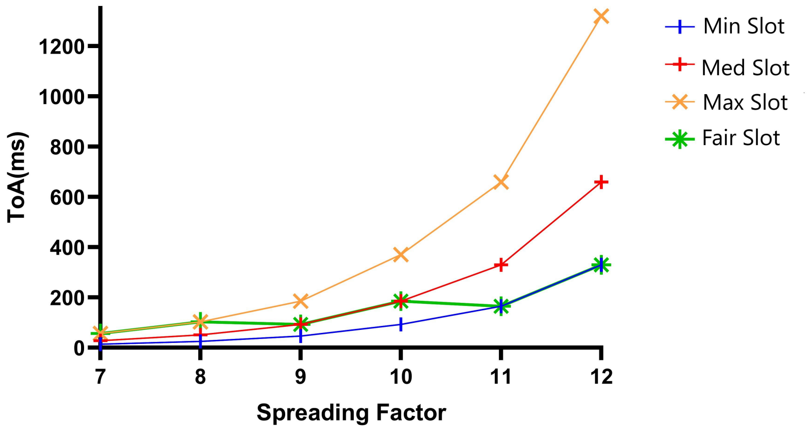


Figure 6.3: The Length of Time Slot

6.4 Network System

The scenario envisions a private LoRaWAN deployment featuring one gateway and several end devices, all operating in balance without interference from other LoRaWAN deployments or technologies in the different frequency band channels. This section theoretically examines this tradeoff to determine the packet length that minimises total energy use. Initially, the bit error rate (BER) of the LoRa modulation corresponds to a certain spreading factor f and is formulated as the equation 6.1 in [165].

$$P_{f,\mathrm{BER}} = \mathcal{Q}\left(\frac{\log_{12} f}{\sqrt{(2)}}\frac{E_b}{N_0}\right) \tag{6.1}$$

In this context, E_b/N_0 represents the ratio of energy per bit to the noise power spectral density, while $Q(x)$ refers to the Q-function. E_b/N_0 can be transformed into signal-to-noise ratio (SNR) as demonstrated in [166]:

$$\begin{aligned} E_b/N_0 = \mathrm{SNR}_f - 10\log\frac{b}{2f} - 10\log f \\ -10\log c + 10\log b \end{aligned} \tag{6.2}$$

The bandwidth and coding rate are denoted by b and c, respectively, while the signal-to-noise ratio (SNR) limit per spreading factor f is determined by SNR_f. These limitations are shown by the packet error rate expressed as 6.1, in [167].

$$P_{f,\mathrm{PER}} = 1 - (1 - P_{f,\mathrm{BER}})^{8\left(Pkt_f\right)} \tag{6.3}$$

According to equation 6.3, a packet is considered corrupted if one or more of its bits are corrupted. This assumption is based on the assumption that the bit errors are distributed independently and remain consistent throughout the packet. In spite of the fact that this assumption may not always be accurate in practice, it is a sensible strategy since it produces the worst-case scenario for the packet error rate. In equation 6.3, a packet's payload length plus the MAC header's length are denoted by the variable Pkt_f. According to equation 6.4, it is possible to express the anticipated number of retransmissions as given in [3].

$$RT_f = \sum_{n=1}^{\infty} P_{f,\mathrm{PER}}^{n} = \frac{P_{f,\mathrm{PER}}}{1 - P_{f,\mathrm{PER}}} \tag{6.4}$$

Given these circumstances, it is possible to compute the amount of energy that is required to transmit the complete buffered data of size X by using.

$$E_f = (1 + RT_f)\left\lceil \frac{X}{Pkt_f} \right\rceil ToA_f IV \tag{6.5}$$

Where the ToA_f represents the transmission time required to send a packet of length Pkt_f on frame, belonging to spreading factor f, while I and V denote the mean current and voltage in the transceiver chip throughout the transmission process, respectively.

The process is separated into stages of normal LoRaWAN. There are two stages to LoRaWAN: the joining stage and the data transmission stage. There can be a non-mandatory stage when the gateway sends acknowledgements. As part of the joining process, the nodes must first register with the gateway by exchanging a set of keys. These keys serve two purposes: First, to ensure the join request is authorized. Second, to make data encryption easier. The keys exchange, nodes periodically wake up, read data by sensors, and send a data packet across a secure channel. In FF-LoRa, transmissions are scheduled to avoid collision-prone periods by dividing the time slots effectively. Moreover, FF-LoRa adds a new final phase when synchronisation and acknowledgement transmission/reception happen. Figure 6.4 shows the stages, and this section describes their functions in depth. The following is how a node can join a LoRaWAN network via the Over-The-Air-Activation (OTAA) protocol, according to the most recent specification:

$$join - request \;\; = [JoinEUI|DevEUI|DevNonce] \tag{6.6}$$

In its join request, the node includes its unique identification (DevEUI), a random application ID (JoinEUI), and a 2-octet nonce (DevNonce). In response, the network server will send a join-accept message similar to form 6.7:

$$join - accept = [JoinNonce|NetID|DevAddr|DLSettings|RxDelay] \tag{6.7}$$

$DevAddr$ is the address of the end device, $NetID$ is the network identification, and $JoinNonce$ is a device-specific counter that should never be repeated. Whenever a gateway gets a join request in FF-LoRa, it must provide a timeslot to the joining node. With each new join request, the gateway adds one to the total number of reserved slots (per SF), which starts at slots 0, 1, 2 and so on, up to the maximum number of assignable slots. While it is possible to directly transmit the associated slot to the node (for instance, include it in the join response), doing so would need many modifications to the server- and node-side registration protocols.

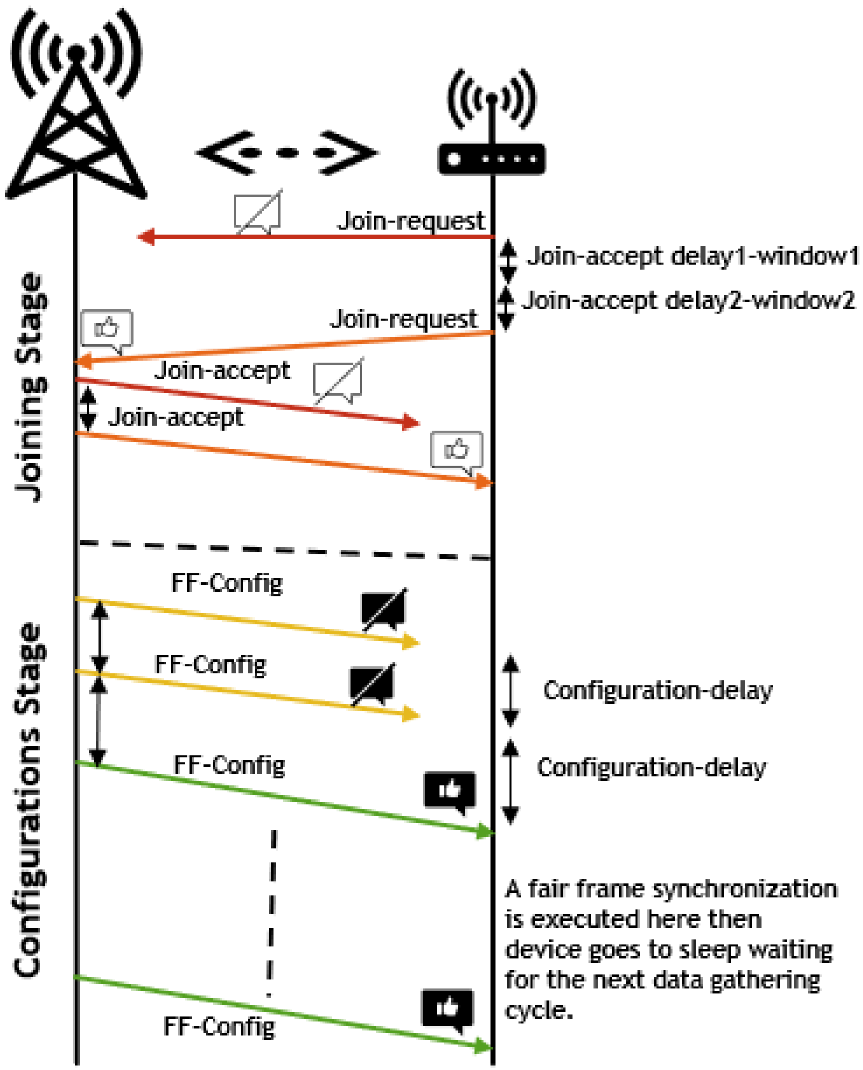


Figure 6.4: The joining and synchronisation sequence

6.4.1 Fair Frame LoRa

The term "fair" here refers to allocating nodes with a high data rate spreading factor to a narrow bandwidth and nodes with a low data rate spreading factor to a wide bandwidth, thereby achieving a balance between nodes in transmission time, which results in an approximated the frames lengths then approximation of energy consumption in the network. For instance Figure 6.3 shows that " Min slot is the collection time with BW500kHz setting, Med slot collection time with BW 250kHz, and Max slot is the collection time with 125kHz, while fair slot comes from our technique. FF-LoRa is a meticulous scheduling method designed to synchronise transmissions for dependable and energy-efficient data collecting. Data gathering occurs at predetermined intervals recognised by the gateway and the end devices. To calculate the schedule for each data collecting period, the gateway must ascertain the quantity of end devices with data to send and evaluate their route loss. The gateway thereafter distributes the schedule and synchronises all end devices to a uniform time reference. The computation and dissemination of the schedule, together with the maintenance of synchronisation, occur in two distinct stages, as demonstrated in Figure 6.4.

FF-LoRa substitutes the conventional simple random access mechanism employed by LoRaWAN with a coordinated medium access strategy. Network devices are synchronised, and transmissions are planned. While coordinated access has been previously examined in the broader context of wireless networks, the proposal introduces a novel perspective owing to the distinctive attributes of LoRaWAN. For unlicensed networks without a listen-before-talk strategy, regulatory duty-cycle constraints limit LoRaWAN transmissions [168]. LoRaWAN gateways may decode up to 8 concurrent broadcasts if they utilise distinct channels and/or spreading factors, although interspreading factor interference may occur owing to LoRa's poor orthogonality [105]. Furthermore, downlink broadcasts may occur just subsequent to uplink transmissions [169]. These unique qualities make scheduling and synchronisation difficult, which have not been addressed in time-coordinated networks [170] or fair frame in LoRaWAN [171]. FF-LoRa schedule design employs six parallel frames, one for each spreading factor, two for each bandwidth and one frame for each frequency channel, with two channels for spreading factor 11 and two for spreading factor 12 as illustrated in Table 6.1. This technique minimises the interval time of the beacon because the maximum collection time is determined by a spreading factor of 12. This minimisation results from the combination of SF12 and a bandwidth of 500 kHz, as illustrated in Figure 6.5. The allocation of channels and transmission powers is designed to minimise the effects of faulty spreading factor orthogonality.

Table 6.1: Frequency channels plan for every spreading factor

N	SF	BW kHz	Frequency
1	7	125	868.10 - 868.30
2	8	125	868.50 - 868.70
3	9	250	863.2 - 865
4	10	250	863.2 - 865
5	11	500	867.5,872.1
6	12	500	867.5,872.1

6.4.2 Fair Frame LoRa Scheduling

FF-LoRa proposes that time is divided into intervals, and each interval is divided into slots. Each slot must be sufficiently elongated to support a single transmission, necessitating various slot dimensions contingent upon the corresponding packet size and transmission duration per SF. The planned frame is a two-dimensional array with six rows, one for each SF, with each row containing a list of slots. The function of a scheduling algorithm is to determine the optimal allocation for each node or transmission to reduce the overall data-collecting time. To do this, transmissions with varying SFs may occur simultaneously, but those with identical SFs are processed sequentially, hence reducing the risk of collisions. Generally, if the airtime for an SF is ToA_f and the duty cycle is 1%, the minimum period per node is 100 ToA_f, and an additional $Z_f = ToA_f * 99 + 2g_f$ nodes may have their transmissions scheduled concurrently, where g_f represents the guard time in a slot. If more than Z_f nodes are assigned to spreading factor f, the schedule for f is prolonged. This has the drawback of diminishing the transmission rate.

The FF-LoRa methodology orchestrates LoRaWAN signals to enhance and equalize data-collecting time efficiency and reduce total energy usage to extend the network lifespan. LoRa transmissions are influenced by several technology-dependent parameters, such as duty cycle and different spreading effects. These aspects provide intriguing trade-offs in the construction of the timetable. The following sections discuss these trade-offs and offer allocation techniques for the transmission parameters.

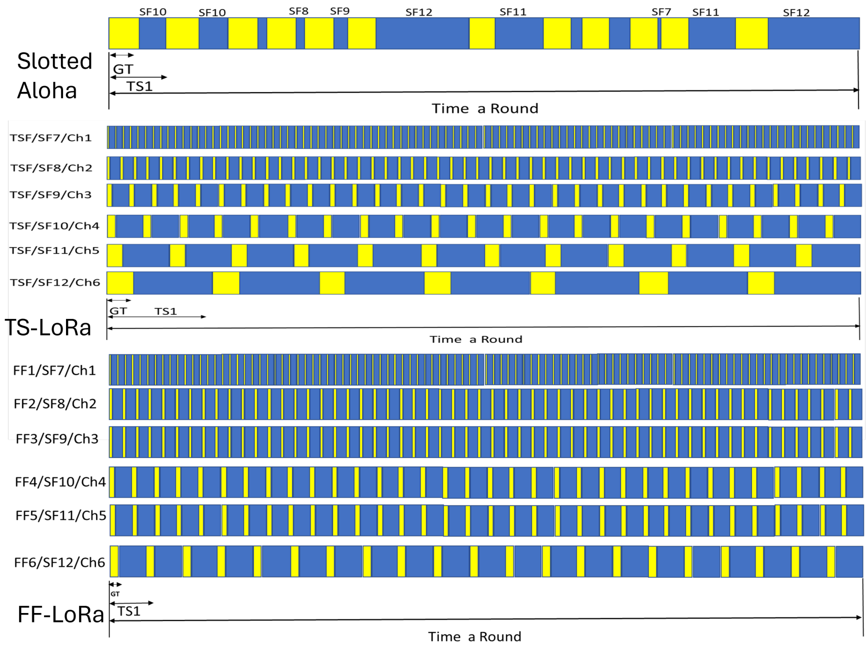


Figure 6.5: The Structure of FF-LoRa

6.4.3 Fair Frame LoRa Synchronization

Scheduling and synchronization avoid most collision conditions, such as in the equation 6.8, to obtain successful transmission.

$$C_{pckt}(p_1,p_2) = \begin{cases} 1 \quad if \quad (O(p_1,p_2)C_{fr}(p_1,p_2)C_f(p_1,p_2) \\ \qquad\quad C_{pw}(p_1,p_2)C_t(p_1,p_2)) \\ 0 \qquad \text{else} \end{cases} \tag{6.8}$$

However, in FF-LoRa, similar to all time-based scheduling algorithms, the nodes are regularly synchronised by the gateway in accordance with a global clock. Due to potential drift in the nodes' clocks, guard intervals are implemented between consecutive broadcasts to prevent overlap between the current and subsequent transmissions. The used guard time is contingent upon the frequency of node synchronisation with the global (gateway-based) clock and certain physical attributes of the device crystals.

$$\text{Fair frame } = \begin{cases} 100 * ToA_f, & \text{if } n \leq \left\lceil \frac{100ToA_f}{ToA_f+2g} \right\rceil, \\ n\left(ToA_f + 2g\right) + T_{SACK}, & \text{if } n > \left\lceil \frac{100ToA_f}{ToA_f+2g} \right\rceil, \end{cases} \quad (6.9)$$

where n represents the number of nodes, ToA_f is the size of the time slot in the frame of spreading factor f, which is the time on air of Pkt_f,$Tsack$ is the final time slot reserved for acknowledgement, and the g is the guard time as explained previously.

6.4.4 Fair Frame LoRa Algorithm

The standard LoRaWAN spreading factor allocation algorithm effectively addresses the receiver sensitivity constraint by typically assigning the lowest feasible spreading factor. This approach has the potential to reduce energy consumption; however, it may result in the overutilization of specific spreading factors. This may result in a schedule that is unbalanced and less than optimal for data collection time. Consequently, the goals of reducing energy consumption and collection time result in conflicts regarding the allocation of the spreading factor. To address this issue, the FF-LoRa Algorithm is proposed, assuming that the gateway knows the number of nodes N and the quantity of data they send. Every node that asks to join the network synchronises with the gateway's clock and then returns to sleep mode. It will wake up at a certain moment to get scheduling information. The scheduling algorithm operates in a greedy online manner, aiming to minimise data-gathering time and energy usage while adhering to duty-cycle constraints.

Initially, the algorithm categorizes nodes based on path loss into three distinct groups: minimum, medium, and maximum. In the subsequent step, the Received Signal Strength Indicator (RSSI) of each node is evaluated to ascertain whether it exceeds the minimum sensitivity threshold defined in equation 6.10.

$$S_f = -174 + 10log_{10}b + NF + SNR_f \tag{6.10}$$

The initial term represents the thermal noise for a 1 Hz bandwidth, while NF signifies the receiver noise figure. The receiver sensitivity will impact the allocation of the spreading factor, as a device must maintain an RSSI that exceeds the receiver sensitivity linked to the respective spreading factor. If the RSSI surpasses this threshold, the algorithm categorises the node according to the appropriate frame. It then schedules the node while incorporating two additional guard times for each slot. Furthermore, the algorithm equips the node with all pertinent information, including frame number, slot number, spreading factor, bandwidth, transmission power, number of channels, and packet size. In the scenarios where the total number of nodes exceeds 100, the algorithm employs equation 6.9 to aggregate the nodes into each frame until the final node. This process is followed by adding the last slot to each frame to facilitate acknowledgement. The fair frame technique equalizes the size of the packet approximately, thereby extending the network lifespan for data collection during scheduled transmissions at optimal times rather than transmitting data immediately upon generation. The next section shows the impact of the FF-LoRa Algorithm compared to conventional studies.

Algorithm 4 Fair Frame-LoRa Algorithm

```
Input  : N nodes amount, and max dist.
Output: Ch, TP, SF, BW, CR, FS.n.FF.n settings for each i of the N nodesToA_i
        and k for each zone Processed list.
PtxLevel = [ ], SF = [ ], b_f = [ ], Ch = [ ], Zone = [ ], Sen = [ , ] FSet[f,b_f ,cr
 ,tp, g, FS.n ,FF.n, ]
/* Assign nodes to best gateway                                        */
Sort N by RSSI /* Sort Node n by PLoss                                  */
while i ≤N do
    if RSSI[i] > MinSens then
        for j ← 0 to MFF do
            /* assign parameters setting to set[i]                     */
            FSL_j = ToA(SF[j],b_j ,cr ,pz) minFFL_j = ToA(FS[j],b_j ,cr ,pz)/DC
            if RSSI[i] > Sen[j] then
                if FFL_j < 100 * ToA(f_j ,b_j ,cr ,pz) then
                    FFL_j = 100 * ToA(f_j,b_j,cr,pz)+ToA(f_j ,b_j,cr,pz)+2*g
                     FSi ← FSL_j
                     SFi ← fj
                     Chi ← Chz
                     Z_f.append([k] + 1)              // count n in each zone.
                else
                    FFL_j = FFL_j + ToA(SF[j],b_j ,cr ,pz) +2*g
                end
                if FFL_j < minFFL_j then
                    minFFL_j = FFL_j
                end
            end
        end
    else
        // Update Node's Transmission power
        TP[i] = TPwLevel[]+ = 1 RSSI[i] = TPwLevel[] − PLoss + GN
         Go to step 6Eng[i]← CalculateEnergy
    end
    TotalEng = Sum(Eng[i])
     i+ = 1
end
return Setting of Each Node
```

Table 6.2: System parameters values for evaluation

Parameter	Value	Comments
N	100 - 1000	Network Size
f	7 to 12	Spreading Factors
$d0$	40 m	Initial Distance
λ	2.32 dBm	PLoss Exponent
$PL_{Env}(d0)$	127.41	Ploss of Initial Distance
$TPLevel$	2 dBm to 14 dBm	Transmission Power
cr	4/5	Coding Rate
b	[125,250,500]kHz	Bandwidth
Area	1000 m^2	
CF	[860, 864, 868]	Carrier Frequency(MHz)
T(s)	7h	Simulation Time
τ	45 min	Round Time

6.5 Evaluation

This section evaluates and assesses the performance of the FF-LoRa model in the context of time-slotted communications within LoRa networks. A simulation tool was developed using Simpy to validate this chapter, incorporating the log-distance path loss model of LoRaSim [131] derived from real environment measurements. Consequently, a square deployment area with a side length of 1000 m contains a variable number of nodes that are randomly and uniformly distributed. The ZBMG-LoRa uses a path-loss model relevant to a smart city context, characterised by rapid signal attenuation [131]. It analyses the performance of time-slotted scheduling heuristics, specifically TS-LoRa [23], in comparison to a Pure Aloha-based approach, which represents the standard LoRaWAN, alongside the FF-LoRa solution for nodes counts ranging from (100 to 1000).

6.5.1 Packet Deliver Ratio

The Packet Delivery Ratio (PDR) is the proportion of total received packets that meet the gateway sensitivity criteria. In a centralized network, the server has better knowledge of the network, resulting in more precise distribution of SFs and other transmission parameters. The results are shown in Figure 6.6. FF-LoRa performs strongly, achieving a 96% PDR and exhibiting similar frame sizes across certain spreading factors 7, 8, 9, and 11. In contrast, LoRaWAN has the lowest PDR due to nodes randomly selecting transmission power levels and spreading factors being determined by a bounded random variable. Additionally, the non-confirmable ALOHA-based method did not achieve a PDR exceeding 68% due to a high incidence of collisions. On the other hand, the PDR of TS-LoRa is approximately 85%, as all nodes initiate their traffic using SF 7 to 12, thanks to the time slot technique.

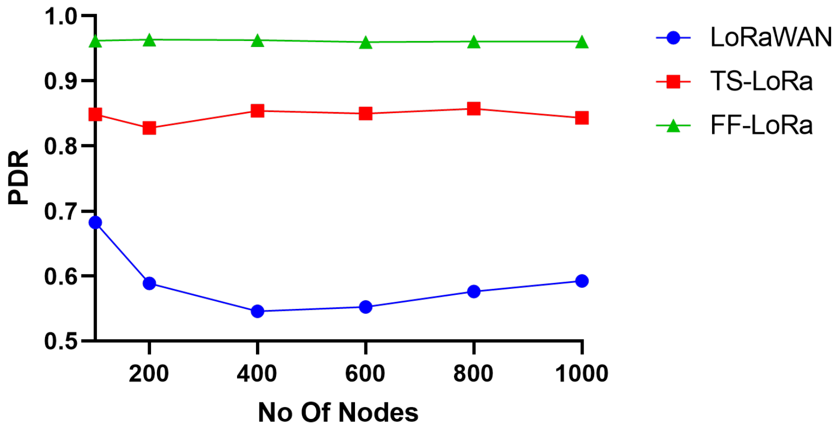


Figure 6.6: The Packet Delivery Ratio of FF-LoRa

6.5.2 Energy consumption

Consumed energy is one of the most significant metrics used to evaluate the approach because it relates to the life span of the device and network. As a function of the total number of nodes, Figure 6.7 illustrates the total amount of energy that is required by nodes in order to effectively transmit packets. Unsurprisingly, LoRaWAN has the greatest energy usage possible since it experiences the highest data collection time and highest lost packets as in Figures 6.9 and 6.10, respectively. In contrast, the TS-LoRa protocol has a high energy consumption rate as the network density grows. This is because the protocol consumed more power due to using high SF 10 and 11 massively compared to low SF. FF-LoRa uses low SF more than TS-LoRa, utilising a fair frame technique in four SFs with insched in SF 10, 12. As a result of having the lowest likelihood of collisions, the FF-LoRa protocol is able to achieve the lowest energy usage available. Furthermore, the level of energy consumption of nodes is slightly raised with the network density. This is due to the effective utilisation of LoRa transmission parameters and the prudent allocation of timeslots, which, therefore, results in a reduction in the number of lost packets.

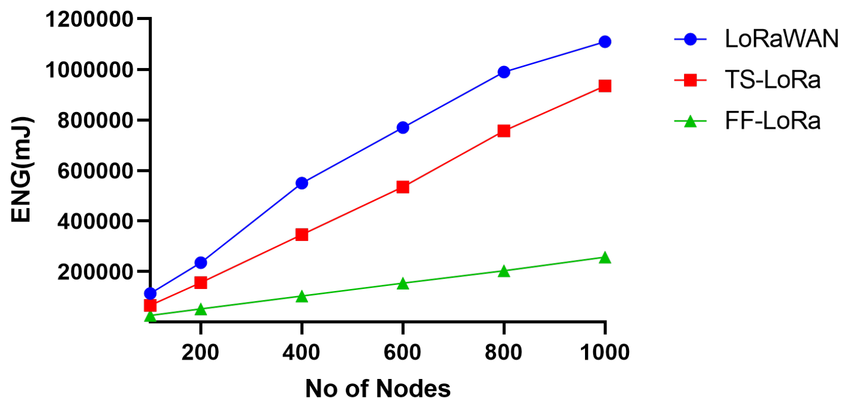


Figure 6.7: Energy Consumption of FF-LoRa.

6.5.3 Collection Time

The collection time is influenced by the longest frame and duty cycle. The effectiveness of FF-LoRa, which allows for collision-free transmissions, significantly improves data collection time as illustrated in Figure 6.9. When utilizing LoRaWAN, the performance shows at least a tenfold increase. Although TS-LoRa exhibits superior performance, it still falls

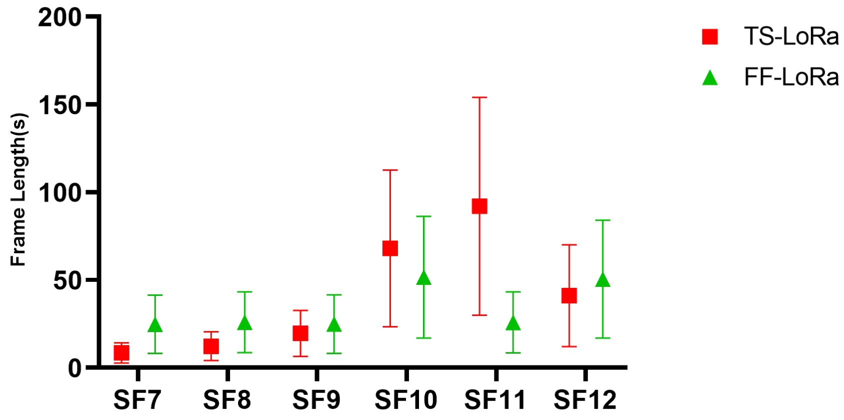


Figure 6.8: Frame Length vs Spreading Factor

short of achieving a completely collision-free method. This highlights the advantages of fair-frame LoRa communications, especially as the number of nodes increases. By scheduling transmissions across different slots and spreading factors, data collection time is substantially reduced compared to the non-scheduled approach used by TS-LoRa.

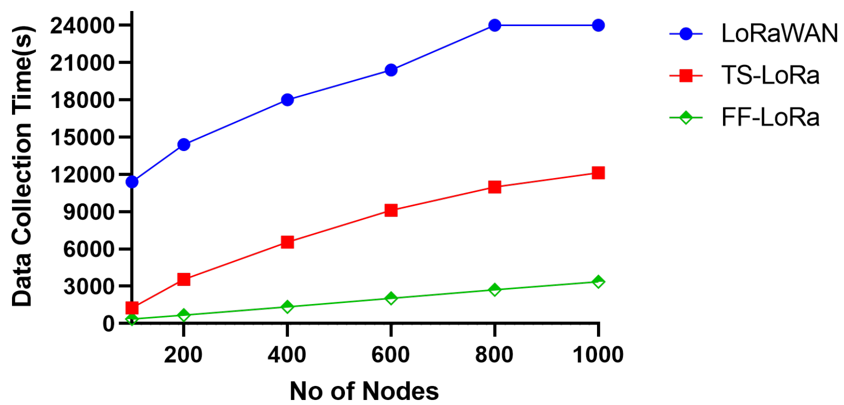


Figure 6.9: The Data Collection Time

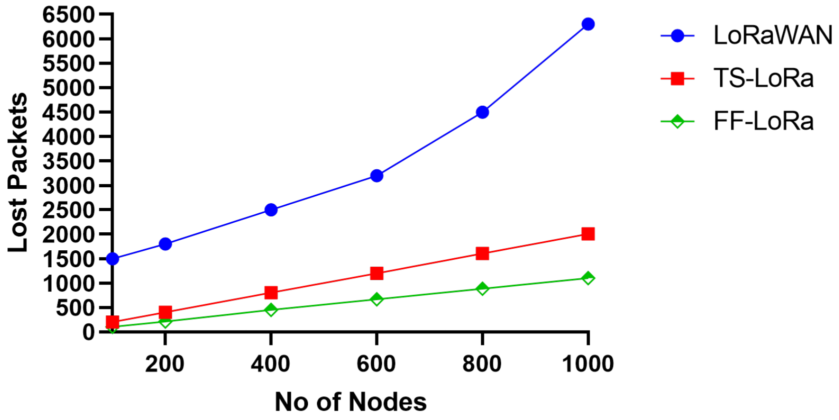


Figure 6.10: Lost Packets

6.5.4 Network Life-spend Metric

This section analyses how altering the frequency of data collection (periodicity) directly impacts energy usage and device lifetime. These effects are closely tied to the flexibility of the data collection delay. The used algorithm collects data from a network with 1000 devices and varies the frequency of data collection from 1 to 24 hours. The findings are shown in Figure 6.11 the FF-LoRa schemes outperform LoRaWAN and TS-LoRa in terms of device lifetime and data collection time, as depicted in Figure 6.9. This improvement is achieved without compromising the overall Packet Delivery Ratio (PDR) for all the different data collection frequencies. It is important to note that at this network size, LoRaWAN barely transmits any data, highlighting the scalability issue of Aloha-based systems for the confirmable traffic type.

6.6 Chapter Summary

This chapter introduces FF-LoRa, a novel approach to fair-frame LoRa communications within the LoRaWAN framework. FF-LoRa facilitates

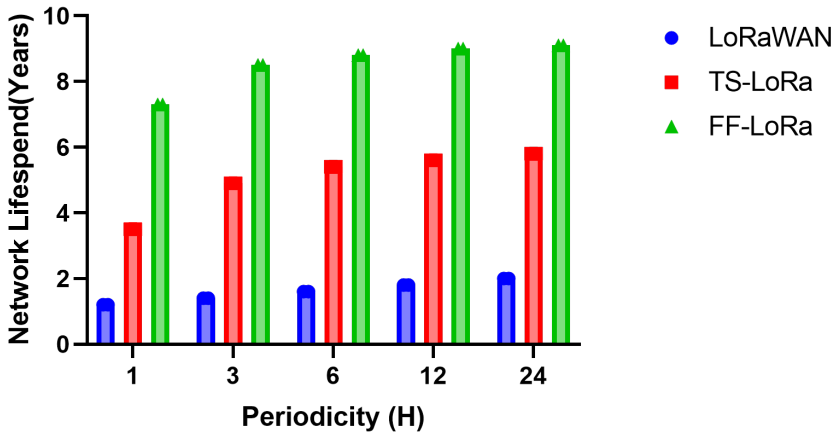


Figure 6.11: Network Lifespan

concurrent transmissions through the utilisation of distinct spreading factors, thereby avoiding collisions, and organises acknowledgements, addressing two significant bottlenecks present in standard LoRaWAN. FF-LoRa facilitates the self-organisation of time slot schedules among nodes within frames. This algorithm assigns unique slot numbers to the addresses of nodes established during the join phase. The simulation conducted compares FF-LoRa with two alternative transmission methods. The findings indicate that FF-LoRa demonstrates effective scalability, achieving nearly 96% data delivery and exceeding eight years of battery life, regardless of transmission type and network size. FF-LoRa is characterised as a fair frame and exhibits scalability, distinguishing it from other time-slotted approaches for LoRaWAN discussed in the literature. Furthermore, FF-LoRa allocates the final slot in each frame for transmitting the "ACKS" packet, which is responsible for time synchronisation and acknowledgements. In the acknowledgements process, the network server consolidates multiple acknowledgements into a single packet to confirm receptions from all slots simultaneously. All confirmable applications incur an additional energy cost to maintain acknowledgements. Nonetheless, the simulation results indicated that this cost is lower than that of LoRaWAN when accommodating confirmable traffic. The next chapter 7 will conclude the whole thesis and discuss the limitations and open direction for future work.

Chapter 7

Conclusion and Future Work

7.1 Thesis Summary

This chapter highlights the key conclusions drawn from the research presented in this thesis. The Thesis introduced specific novel elements of optimal allocation settings and resource management MBMD-LoRa, MBMZ-LoRa in terms of single gateway network, ZBMG-LoRa in terms of multi-gateway network and FF-LoRa in terms of TDMA in LoRaWAN network. LoRaWAN presents distinct design parameters and trade-offs, such as extended transmission range, reduced power consumption, and limited duty cycle, differentiating them from traditional short-range wireless sensor networks. This thesis proposes several novel protocols and improvements aimed at enhancing the scalability and power efficiency of LoRa while also addressing resource management within networks. It takes into account the limitations, including restricted downlink capability and constrained duty cycles. The thesis primarily examined LoRaWAN; however, its conclusions are applicable to other LPWAN technologies due to their shared architecture and limitations with LoRaWAN. The proposals have addressed multiple aspects of the LoRaWAN protocol stack, encompassing the MAC layer through to the application layer. Furthermore, the contributions have been disseminated in multiple peer-reviewed conferences and journals by IEEE and Springer. The following sections in this chapter summarise the concluding remarks drawn from the thesis and suggest directions for future research work.

7.2 Concluding Remarks

The research presented in this thesis has demonstrated the possibility of developing an accurate framework for a scalable LoRaWAN network. The research effort was carried out in five sequential phases. First, to understand the opportunities and limitations of ADR and TDMA in LoRaWAN by experimentally calibrating between low power consumption and a high packet deliver ratio. The second phase focused on developing an adaptive data rate scheme to enhance the LoRaWAN capacity signal gateway network. The third focus of this thesis has been to prevent overlapping between gateways and improve ADR in multi-gateway LoRaWAN networks. Finally, a fair frame time slot and the enhancement of battery lifespan have been the capstone of the research effort. The following sub-section outlines the findings of the thesis.

7.2.1 MBMD-LoRa Scalable LoRaWAN for Internet of Things: A Multi-Band Multi-Data Rate Approach

The calibration results reported in Chapter 4, which achieved the second research objective in section 1.3.2, confirm that the proposed solution to the challenge of LoRa network size, optimising the number of nodes, packet delivery ratio, and energy efficiency. A novel approach has shown that an optimal solution exists and is unique for each Slim Data Rate. Furthermore, we have shown the effectiveness of MBMz-LoRa, which builds upon MBMD-LoRa and operates under the framework of six zones for all LoRa nodes. The MBMD-LoRa algorithm has improved the data rate ratio, with significant increases observed in data rate levels 1 to 6, while data rate level 0 remains unchanged. The doubling of the data rate results in a reduction of the time-on-air packet size and enhances energy efficiency, as the increased data rate leads to a decrease in packet transmission time (ToA). This also includes a reduction in collisions attributed to packet size, which lowers transmission power and the need for retransmission of packets. The diversity of SF within the cell represents a crucial enhancement, as it mitigates collisions among nodes, thus conserving energy by obviating the necessity for retransmission of *Pckt*. The simulation results indicate that the proposed method achieves a higher delivery ratio and lower energy consumption compared to conventional studies.The new proposal determines spreading factors, transmission strengths, frequency channels, and bandwidth for LoRaWAN devices. The idea addressed the scalability issue of LoRaWAN by mitigating collisions. The numerical results from the performance assessments indicated that the new plan exhibits effective scalability, attaining over 49% data delivery, while energy efficiency is projected to exceed 30%, irrespective of traffic type and network size. This is in contrast to inadequate scalability, poor data transmission, diminished energy efficiency and data traffic in the standard LoRaWAN.

7.2.2 ZBMG-LoRa Scalable LoRaWAN for Internet of Things: A Zone-based Multi-Gateway Multi-Data Rate Approach

A novel framework has been presented in Chapter 5 for facilitating scalable communication in long-range IoT networks, which achieved the third research objective in section 1.3.2. The ZBMG-LoRa algorithm integrates the Gateways Allocation and Spreading Factor (GASF) components. The LoRa nodes in this algorithm demonstrate behaviour aligned with the information supplied by the network server. The ZBMG-LoRa algorithm has improves the data rate ratio by eliminating the use of SF 11 and 12. This modification has reduces the packet transmission time and enhanced energy efficiency, as an increased data rate correlates with a decrease in packet time. This also includes a reduction in collisions attributed to packet size, which leads to decreased transmission power and fewer retransmissions for packets. The variety of channels within the cell represents a crucial enhancement, as it mitigates collisions among nodes, thus conserving energy by obviating the necessity for retransmitting $Pckt$. The simulation results indicate that the proposed method achieves a higher packet delivery ratio and lower energy consumption in comparison to the original protocol and previous studies. A significant quantity of nodes within the overlapping coverage area must adjust their configurations to enhance network throughput, highlighting the trade-off between fairness and efficiency.

7.2.3 A Novel Fair Frame Time Slot LoRaWAN IoT

This section presents FF-LoRa, an innovative method for fair-frame LoRa communications in the context of the LoRaWAN framework, which achieved the fourth research objective in section1.3.2. FF-LoRa enables simultaneous transmissions by employing different spreading factors, thus preventing collisions, and manages acknowledgements, effectively addressing two major bottlenecks in conventional LoRaWAN. FF-LoRa enables the self-organisation of time slot schedules among nodes within frames. This algorithm allocates distinct slot numbers to the addresses of nodes created during the join phase. Simulations were conducted to compare FF-LoRa with two alternative transmission methods. The results show that FF-LoRa exhibits significant scalability, attaining approximately 96% data delivery and surpassing eight years of battery life, independent of transmission type and network size. Chapter 6 is defined as a fair frame and demonstrates scalability, setting it apart from other time-slotted methods for LoRaWAN presented in the literature. The FF-LoRa is capable of supporting applications that require moderate transmission interval times, including industrial automation, smart transportation, and smart agriculture.

7.2.4 Limitations

Despite the advantages of test-based validation, which we plan to present to the LoRaWAN alliance or Semtech for adoption and funding, several considerations have led us to rely solely on simulation. These considerations include the following.

- **Deployment Cost**

  Implementing hundreds or thousands of physical node sensors to meticulously assess network scalability poses considerable cost and logistical challenges. The expenses related to acquiring, installing, energising, and maintaining a substantial quantity of devices are sometimes prohibitive for the majority of research and development initiatives. Network simulation appears as an essential and economical solution. Simulation enables researchers and engineers to model and analyse the behaviour of several nodes by constructing a virtual version of the network, therefore eliminating the costs associated with actual hardware. It provides unmatched flexibility to evaluate diverse topologies, traffic patterns, and failure scenarios at a scale that would be impractical or unfeasible to replicate in reality, thus yielding essential insights into network performance and scalability within a controlled and cost-effective setting.

- **Restrict Novelty**

  Certain writers contend that excessive dependence on hardware-based experiments may unintentionally limit innovation and creative expression in scientific inquiry. This viewpoint posits that the limitations of physical hardware—such as exorbitant pricing, insufficient customisability, and the inherent challenges of reconfiguring complex systems—can hinder the pursuit of really unusual concepts [172]. Researchers may be gently directed into more predictable or incremental enquiries that align with the current capabilities of their equipment, rather than exploring high-risk, high-reward investigations that need custom or non-existent instruments [173]. In domains where advancement relies on examining an extensive parameter space or evaluating unconventional ideas, the rigid characteristics of hardware might pose a considerable constraint, while simulation provides boundless, risk-free adaptability to investigate "what if" situations that are physically or monetarily unfeasible [172] . Thus, while hardware is crucial for testing real-world events, some academics argue that it might confine research to existing paradigms, restricting the unrestricted, exploratory thinking that often results in groundbreaking findings [173].

7.3 Future Work and Recommendations

Following the work undertaken in this thesis, LoRa and LoRaWAN technologies exhibit significant potential for future development, driven by increasing adoption across various industries globally. Nonetheless, the technology continues to face various constraints and limitations that require resolution. Chapters 3,4,5 and 6 presented various techniques for addressing the challenges associated with LoRaWAN deployments; however, the proposed approaches require further enhancement to improve LoRaWAN performance and present this idea to the LoRaWAN Alliance or Semtech for adoption and funding. This chapter highlights several open challenges associated with LoRaWAN technology, based on the prior analysis and investigations of research issues and recently proposed methods discussed in Chapters 3.

- **scalability**. Resource management schemes are utilised to align the transmission windows of end devices with the reception windows of gateways. The RX windows of the GWs are not consistently accessible, as TX must be activated to confirm the receipt of data. Furthermore, energy efficiency mandates prevent EDs from maintaining continuous openness of their TX and RX windows. Consequently, this discrepancy must be addressed by taking into account the network density, which limits the effectiveness of these methods in improving LoRaWAN capacity. Consequently, the logical and frequency channels were organised to facilitate the simultaneous transmission of multiple EDs. Promising results are observed in this context through the application of smart resource assignment schemes. Mathematical tools, including game theory, can effectively manage resources by modelling interactions between energy distributors EDs and grid workers GWs, utilising different game types based on specific target scenarios and Quantifying the server-side computational complexity of the proposed algorithms.

- **Carrier Sensing Energy-Efficient**. Future work could be undertaken to explore the possibility of utilising the listen-before-talk method to improves LoRaWAN channel efficiency. Using the same SF and signal characteristics, EDs can detect the medium and determine whether the channel is idle or occupied by another TX. Carrier sensing is energy-intensive therefore it should be used cautiously with ED batteries. However, long-range communication's extended time-on-air reduces carrier sensing systems' efficacy, therefore multiple channel sensing may be needed to maximise its benefits. Future medium access protocols should offer multi-hop data TX. Considering a fraction of hidden nodes with potential collision avoidance over sensing ranges, adapted CSMA/CA protocols were recommended. Despite attempts, energy consumption is the biggest obstacle to LoRaWAN CSMA implementation.

- **Machine Learning for MAC**. LoRaWAN advocates for slotted MAC protocols rather than pure ALOHA-like protocols due to their limited scalability. Due to LoRa's features and sub-GHz ISM bands' duty cycle limits, building an effective time-slotted MAC protocol is difficult. Additionally, decoding algorithms like the CRC may assist decipher symbols of many colliding frames. Due to LoRaWAN duty cycle constraints and limited downstream connections, synchronising and scheduling the TX proved more difficult. To prevent these issues, EDs cooperate to self-organise their TXs and avoid clashes over node needs and communication circumstances using autonomous and distributed scheduling techniques. Deep reinforcement learning offers a fresh research approach to this problem. A DRL agent may be created and trained offline to effectively handle MAC layer resources aboard EDs. To enable efficient communication while considering other EDs and LoRaWAN protocol limitations, local decision-making on MAC layer resources is allowed.

- **Time Slot Frame** Several of the concerns outlined in TSF limitation sections are addressed or mitigated by current implementations; nonetheless, a number of them remain unsolved. Table 3.5 outlines how various methods address the respective difficulties, whilst the following paragraph provides further information. Multiple acknowledgements are grouped into a single brief slot to circumvent limited downlink capacity[174]. This technique reduces the amount of extra overhead and regulates the duty cycle resources more effectively. Downlink bottlenecks that may otherwise result in severe delays are avoided via autonomous scheduling techniques. In addition, one of the basic issues is how to support as many LoRa settings as feasible (i.e., various SF/ BW/ CR/ Payloads). Most solutions assume fixed settings for all nodes, which may restrict the flexibility and capability of the application. Multiple SFs are supported by TS-LoRa with the use of extra 1-channel gateways. Multiple independent frames can operate concurrently, allowing for different BW, CR, and payload configurations per SF[175].

All synchronisation methods use a single slot, data transmission slots, or a separate slot. Synchronisation is usually done by calculating the time between the receiver turning on its radio and receiving sync information. This method reduces energy consumption and reduces duty cycle time. All of the offered techniques make use of sufficient guard times in order to accommodate both the extended transmission lengths of LoRa radios and the sparse communication that is the result of duty cycle constraints. The propagation time, which may seem short but is actually quite important, is also factored into the guard timings. Encryption remains a concern, as the majority of systems either disregard it or provide just uplink encryption. The last issue of note is that scalability, and power efficiency is insufficient[176]. There is no roaming mechanism that would allow devices to interoperate across numerous cells. The existing designs include the presumption that this can be achieved by allowing a device to rejoin the network; however, this is wasteful in terms of both the amount of time it takes and the amount of energy that it costs[112].

References

[1] D. KJENDAL (Senet) A. YEGIN (Actility), O. SELLER (Semtech), "Lorawan® regional parameters rp002-1.0.4", 2022. xiv, 34, 73, 76, 82, 83, 111, 139

[2] Eryk Schiller, Andy Aidoo, Jara Fuhrer, Jonathan Stahl, Michael Ziörjen, and Burkhard Stiller, "Landscape of iot security", *Computer Science Review*, vol. 44, pp. 100467, 2022. 1

[3] Khaled Q. Abdelfadeel, Dimitrios Zorbas, Victor Cionca, and Dirk Pesch, "Free—fine-grained scheduling for reliable and energy-efficient data collection in lorawan", *IEEE Internet of Things Journal*, vol. 7, no. 1, pp. 669–683, 2020. 2, 32, 37, 48, 50, 53, 60, 61, 63, 78, 137, 141, 143, 148

[4] Anurag Kumar, D. Manjunath, and Joy Kuri, *CHAPTER 7 - Random Access and Wireless LANs*, pp. 187–241, Morgan Kaufmann, Burlington, 2008. 2

[5] Matheus Araujo Gava, Helder Roberto Oliveira Rocha, Menno Jan Faber, Marcelo Eduardo Vieira Segatto, Heinrich Wörtche, and Jair Adriano Lima Silva, "Optimizing resources and increasing the coverage of internet-of-things (iot) networks: An approach based on lorawan", *Sensors*, vol. 23, no. 3, pp. 1239, 2023. 2

[6] David Kammer, Gordon McNutt, Brian Senese, and Jennifer Bray, Eds., *Chapter 2 - Exploring the Foundations of Bluetooth*, pp. 69–102, Syngress, Burlington, 2002. 2

[7] Shahin Farahani, *Chapter 1 - ZigBee Basics*, pp. 1–24, Newnes, Burlington, 2008. 2

[8] Nicolás López-Vilos, Claudio Valencia-Cordero, Cesar Azurdia-Meza, Samuel Montejo-Sánchez, and Samuel Baraldi Mafra, "Performance analysis of the ieee 802.15.4 protocol for smart environments under jamming attacks", *Sensors*, vol. 21, no. 12, pp. 4079, 2021. 2

[9] Usman Raza, Parag Kulkarni, and Mahesh Sooriyabandara, "Low power wide area networks: An overview", *IEEE Communications Surveys Tutorials*, 2017. 2, 46

[10] Luca Beltramelli, Aamir Mahmood, Patrik Osterberg, and Mikael Gidlund, "Lora beyond aloha: An investigation of alternative random access protocols", *IEEE Transactions on Industrial Informatics*, pp. 1–1, 2020. 3, 28, 30

[11] Halit Uyan?k and Tolga Ovatman, "An investigation of the transmission success in lorawan enabled iot-haps communication", *Internet of Things*, vol. 20, pp. 100611, 2022. 5

[12] A. Sabovic, C. Delgado, D. Subotic, B. Jooris, E. De Poorter, and J. Famaey, "Energy-aware sensing on battery-less lorawan devices with energy harvesting", *Electronics*, vol. 9, no. 6, 2020. 5

[13] Z. Xu, J. Luo, Z. Yin, S. Wang, C. Chen, J. Lin, R. Xiong, and T. He, "Leveraging imperfect-orthogonality aware scheduling for high scalability in lpwan", *IEEE Transactions on Mobile Computing*, pp. 1–18, 2024. 5, 138

[14] Eugen Harinda, Andrew J Wixted, Ayyaz-UI-Haq Qureshi, Hadi Larijani, and Ryan M Gibson, "Performance of a live multi-gateway lorawan and interference measurement across indoor and outdoor localities", *Computers*, vol. 11, no. 2, pp. 25, 2022. 5, 7

[15] T. Elshabrawy and J. Robert, "Capacity planning of lora networks with joint noise-limited and interference-limited coverage

considerations", *IEEE Sensors Journal*, vol. 19, no. 11, pp. 4340–4348, 2019. 6

[16] Mukarram Al-Muhaya, Tawfik Al-Hadhrami, Omprakash Kaiwartya, and David Brown, *A Comprehensive Comparison in Time-Slotted Frame Protocols in LoRaWAN IoT Technology*, 2023. 6, 138

[17] A. Potsch and F. Hammer, "Towards end-to-end latency of lorawan: Experimental analysis and iiot applicability", *2019 15th Ieee International Workshop on Factory Communication Systems (Wfcs)*, 2019. 6

[18] F. Loh, N. Mehling, S. Gei, x00Df, ler, T. Ho, x00Df, and feld, "Simulative performance study of slotted aloha for lorawan channel access", in *NOMS 2022-2022 IEEE/IFIP Network Operations and Management Symposium*, pp. 1–9. 7, 29

[19] Luca Beltramelli, Aamir Mahmood, Patrik Österberg, Mikael Gidlund, Paolo Ferrari, and Emiliano Sisinni, "Energy efficiency of slotted lorawan communication with out-of-band synchronization", *IEEE Trans. Instrum. Meas.*, vol. 70, pp. 1–11, 2021. 7

[20] M. Heusse, C. Caillouet, and A. Duda, "Performance of unslotted aloha with capture and multiple collisions in lorawan", *IEEE Internet of Things Journal*, vol. 10, no. 20, pp. 17824–17838, 2023. 7, 110

[21] B. Yu, Y. Bao, Y. Huang, W. Zhan, and P. Liu, "Modeling and throughput optimization of multi-gateway lorawan", *IEEE Access*, vol. 11, pp. 142940–142950, 2023. 7

[22] Ali Loubany, Samer Lahoud, Abed Ellatif Samhat, and Melhem El Helou, "Joint throughput-energy optimization in multi-gateway lorawan networks", *Telecommunication Systems*, 2023. 7, 106, 108, 130

[23] Dimitrios Zorbas, Panayiotis Kotzanikolaou, and Dirk Pesch, "Ts-lora: Time-slotted lorawan for the industrial internet of things",

Computer Communications, vol. 153, pp. 1–10, 2020. 8, 33, 49, 50, 53, 54, 60, 63, 64, 70, 142, 143, 146, 157

[24] Anna Triantafyllou, Panagiotis Sarigiannidis, Thomas Lagkas, Ioannis D. Moscholios, and Antonios Sarigiannidis, "Leveraging fairness in lorawan: A novel scheduling scheme for collision avoidance", *Computer Networks*, vol. 186, pp. 107735, 2021. 8, 53, 60, 63

[25] Abdulwakil Adekunle Kasali, Caleb Olufisoye Akanbi, Lawrence Olaleye Omotosho, and Ibrahim Kazeem Ogundoyin, "Integrating fairness in current consumption of end devices in time–slotted lora–based wireless sensor network", *Annals of the Faculty of Engineering Hunedoara*, vol. 22, no. 2, pp. 153–162, 2024. 8

[26] C. Shao, O. Muta, K. Tsukamoto, W. Lee, X. Wang, M. Nkomo, and K. R. Dandekar, "Toward improved energy fairness in csma-based lorawan", *IEEE/ACM Transactions on Networking*, vol. 32, no. 5, pp. 4382–4397, 2024. 8

[27] Z. Zhao, W. Gao, W. Du, G. Min, W. Mao, and M. Singhal, "Towards energy-fairness in lora networks", *IEEE Transactions on Mobile Computing*, pp. 1–1, 2022. 8

[28] L. Shangguan K. Jamieson P. Levis B. Ghena, J. Adkins and P. Dutta, "Challenge: Unlicensed lpwans are not yet the path to ubiquitous connectivity", 2019. 14

[29] N. Mangalvedhe R. Ratasuk, B. Vejlgaard and A. Ghosh, "Nb-iot system for m2m communication", 2016. 15

[30] Mads Lauridsen, Istvan Kovacs, Preben Mogensen, Mads Sorensen, and Steffen Holst, *Coverage and Capacity Analysis of LTE-M and NB-IoT in a Rural Area*, 2016. 15

[31] A. Lavric, A. I. Petrariu, and V. Popa, "Long range sigfox communication protocol scalability analysis under large-scale, high-density conditions", *IEEE Access*, vol. 7, pp. 35816–35825, 2019. 15

[32] Zubair Amjad, Kofi Atta Nsiah, Benoît Hilt, Jean-Philippe Lauffenburger, and Axel Sikora, "Latency reduction for narrowband urllc networks: a performance evaluation", *Wirel. Netw.*, vol. 27, no. 4, pp. 2577–2593, 2021. 15

[33] Taghi Shahgholi, Amir Sheikhahmadi, Keyhan Khamforoosh, and Sadoon Azizi, "Lpwan-based hybrid backhaul communication for intelligent transportation systems: architecture and performance evaluation", *EURASIP J. Wirel. Commun. Netw.*, vol. 2021, no. 1, pp. 17, 2021. 15

[34] M. Ballerini, T. Polonelli, D. Brunelli, M. Magno, and L. Benini, "Nb-iot versus lorawan: An experimental evaluation for industrial applications", *IEEE Transactions on Industrial Informatics*, vol. 16, no. 12, pp. 7802–7811, 2020. 16

[35] Ladislav Zemko and Pavel ?i?ák, "Iot and lpwan networks: Increasing efficiency by communication planning", in *2022 45th International Conference on Telecommunications and Signal Processing (TSP)*. pp. 116–121, IEEE. 16

[36] B. Reynders and S. Pollin, "Chirp spread spectrum as a modulation technique for long range communication", in *2016 Symposium on Communications and Vehicular Technologies (SCVT)*, pp. 1–5. 17

[37] Zehua Sun, Huanqi Yang, Kai Liu, Zhimeng Yin, Zhenjiang Li, and Weitao Xu, "Recent advances in lora: A comprehensive survey", *ACM Transactions on Sensor Networks*, 2022. 17

[38] Jansen Liando, Amalinda Gamage, Agustinus Tengourtius, and Mo Li, "Known and unknown facts of lora: Experiences from a large-scale measurement study", *ACM Transactions on Sensor Networks*, vol. 15, pp. 1–35, 2019. 17

[39] T. T. Nguyen, H. H. Nguyen, R. Barton, and P. Grossetete, “Efficient design of chirp spread spectrum modulation for low-power wide-area networks”, *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 9503–9515, 2019. 17

[40] Martin Bor, “Towards the efficient use of lora for wireless sensor networks”, 2020. 19

[41] Pieter Robyns, Peter Quax, Wim Lamotte, and William Thenaers, “A multi-channel software decoder for the lora modulation scheme”, in *International Conference on Internet of Things, Big Data and Security*, 2018. 23, 24

[42] Semtech, “Sx1276/77/78/79 - 137 mhz to 1020 mhz low power long range transceiver”, 2020. 23

[43] Samar Adel Almarzoqi, Ahmed Yahya, Zaki Matar, and Ibrahim Gomaa, “Re-learning exp3 multi-armed bandit algorithm for enhancing the massive iot-lorawan network performance”, *Sensors*, vol. 22, no. 4, pp. 1603, 2022. 24

[44] M. LE GOURRIEREC (Sagemcom) J. CATALANO (Kerlink), R. HOUDE (Senet) and J. SWETINA (NEC) 61 N. SORNIN (Semtech), “Lorawan® multi-package access protocol specification”, 2022. 24, 27

[45] Semtech, “”lorawan specication v1.0.3,”[online]. available: https://www.lora-alliance.org/technology”, 2019. 24, 26, 34

[46] The Things Network., “[online]. available: https://www.thethingsnetwork.org/”. 25, 26

[47] Semetch. Lahoud, “Lorawan network architecture,lora allaincein 2018, url: https://www.lora-alliance.org.”, 2018. 26, 27, 31

[48] Mohammed Jouhari, El Mehdi Amhoud, Nasir Saeed, and Mohamed-Slim Alouini, “A survey on scalable lorawan for massive iot: Recent advances, potentials, and challenges”, *arXiv preprint arXiv:2202.11082*, 2022. 27

[49] Panagiotis Gkotsiopoulos, Dimitrios Zorbas, and Christos Douligeris, "Performance determinants in lora networks: A literature review", *IEEE Communications Surveys Tutorials*, vol. 23, no. 3, pp. 1721–1758, 2021. 28, 51

[50] D. Bankov, E. Khorov, and A. Lyakhov, "On the limits of lorawan channel access", *2016 International Conference on Engineering and Telecommunication (Ent 2016)*, pp. 10–14, 2016. 28

[51] Frank Loh, Noah Mehling, Stefan Geißler, and Tobias Hoßfeld, "Efficient graph-based gateway placement for large-scale lorawan deployments", *Computer Communications*, vol. 204, pp. 11–23, 2023. 28

[52] Nagib Matni, Jean Moraes, Helder Oliveira, Denis Rosário, and Eduardo Cerqueira, "Lorawan gateway placement model for dynamic internet of things scenarios", *Sensors*, vol. 20, no. 15, pp. 4336, 2020. 28, 29

[53] Xianjin Xia, Acm, Yuanqing Zheng, and Tao Gu, "Ftrack: Parallel decoding for lora transmissions", *IEEE/ACM Transactions on Networking*, pp. 1–14, 2020. 28

[54] A. Petroni and M. Biagi, "Interference mitigation and decoding through gateway diversity in lorawan", *IEEE Transactions on Wireless Communications*, vol. 21, no. 11, pp. 9068–9081, 2022. 28, 108, 110

[55] Tommaso Polonelli, Davide Brunelli, Achille Marzocchi, and Luca Benini, "Slotted aloha on lorawan-design, analysis, and deployment", *Sensors*, vol. 19, no. 4, pp. 838, 2019. 29, 30, 50

[56] K. Spathi, A. Valkanis, G. BeletsIoTi, G. Papadimitriou, and P. Nicopolitidis, "Performance evaluation of slotted aloha based iot networks under asymmetric traffic", in *2020 International Conference on Communications, Computing, Cybersecurity, and Informatics (CCCI)*, pp. 1–5. 29

[57] Malak Abid Ali Khan, Hongbin Ma, Syed Muhammad Aamir, and Ying Jin, "Optimizing the performance of pure aloha for lora-based esl", *Sensors*, vol. 21, no. 15, pp. 5060, 2021. 29

[58] J. Ortin, M. Cesana, and A. Redondi, "How do aloha and listen before talk coexist in lorawan?", *2018 Ieee 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (Pimrc)*, 2018. 29, 31

[59] J. Ortin, M. Cesana, and A. Redondi, "Augmenting lorawan performance with listen before talk", *Ieee Transactions on Wireless Communications*, vol. 18, no. 6, pp. 3113–3128, 2019. 29

[60] Francisco Tirado-Andrés and Alvaro Araujo, "Performance of clock sources and their influence on time synchronization in wireless sensor networks", *International Journal of Distributed Sensor Networks*, vol. 15, no. 9, pp. 1550147719879372, 2019. 30

[61] Semtech, "Understanding the lora®adaptive data rate technical paper december 2019", 2019. 31

[62] 2 * Rachel Kufakunesu 1, Gerhard P. Hancke 1 and Adnan M. Abu-Mahfouz, "A survey on adaptive data rate optimization in lorawan: Recent solutions and major challenges", 2020. 31

[63] Slim Loukil, Lamia Chaari Fourati, Anand Nayyar, and K.-W.-A. Chee, "Analysis of lorawan 1.0 and 1.1 protocols security mechanisms", *Sensors*, vol. 22, no. 10, pp. 3717, 2022. 32

[64] M. Rizzi, P. Ferrari, A. Flammini, E. Sisinni, and M. Gidlund, "Using lora for industrial wireless networks", in *2017 IEEE 13th International Workshop on Factory Communication Systems (WFCS)*, pp. 1–4. 32

[65] Rajeev Piyare, Amy L. Murphy, Michele Magno, and Luca Benini, "On-demand lora: Asynchronous tdma for energy efficient and low latency communication in iot", *Sensors*, vol. 18, no. 11, pp. 3718, 2018. 32, 48, 141

[66] J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Low overhead scheduling of lora transmissions for improved scalability", *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3097–3109, 2019. 32, 48, 141

[67] L. Leonardi, F. Battaglia, and L. Lo Bello, "Rt-lora: A medium access strategy to support real-time flows over lora-based networks for industrial iot applications", *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 10812–10823, 2019. 33, 49, 142

[68] Y. Wang, X. Zheng, L. Liu, and H. Ma, "Polartracker: Attitude-aware channel access for floating low power wide area networks", *IEEE/ACM Transactions on Networking*, vol. 30, no. 4, pp. 1807–1821, 2022. 33, 49, 142

[69] Microchip Technology Inc, "Rn2483 low-power long range lora technology transceiver module.", 2015. 34

[70] LoRa Alliance, "Ts2-1.1.0 lorawan backend interfaces specification", 2020. 34

[71] Nicholas Sornin et al., "Lorawan 1.1 specications, tech. rep. 2017", 2017. 34

[72] Semtech Proprietary Confidential, "Long range, low power, multi-band lora® transceiver", 2023. 34, 35, 73, 77, 85, 86, 87, 119

[73] Nikos Kouvelas, Vijay Rao, and Venkatesha Prasad, *Employing p-CSMA on a LoRa Network Simulator*, 2018. 37, 143

[74] Brecht Reynders, Wannes Meert, and Sofie Pollin, "Power and spreading factor control in low power wide area networks", IEEE. 42, 87, 89, 121, 123

[75] O.SELLER A.YEGIN, ""lorawan specication v1.0.4,"[online]. available: https://www.lora-alliance.org/technology", 2020. 43, 74, 107

[76] Nicholas Sornin et al., "Lorawan simple rate adaption recommended algorithm, tech. rep.", 2016. 43

[77] Athanasios Tsakmakis, Anastasios Valkanis, Georgia Beletsioti, Konstantinos Kantelis, Petros Nicopolitidis, and Georgios Papadimitriou, "An adaptive lorawan mac protocol for event detection applications", *Sensors*, vol. 22, no. 9, pp. 3538, 2022. 43

[78] D.KJENDAL (Senet) D.KJENDAL (Senet) O.SELLER (Semtech), A.YEGIN (Actility), "Rp002-1.0.1 lorawan® regional parameters .", 2020. 43

[79] Y. A. Al-Gumaei, N. Aslam, X. Chen, M. Raza, and R. I. Ansari, "Optimizing power allocation in lorawan iot applications", *IEEE Internet of Things Journal*, vol. 9, no. 5, pp. 3429–3442, 2022. 44, 98

[80] M. Slabicki, G. Premsankar, and M. Di Francesco, "Adaptive configuration of lora networks for dense iot deployments", in *NOMS 2018 - 2018 IEEE/IFIP Network Operations and Management Symposium*, pp. 1–9. 44, 56, 81, 117

[81] Gabriel Germino Martins De Jesus, Richard Demo Souza, Carlos Montez, and Arliones Hoeller, "Lorawan adaptive data rate with flexible link margin", *IEEE Internet of Things Journal*, vol. 8, no. 7, pp. 6053–6061, 2021. 44, 97, 129

[82] Laura Scipione Nicola Blefari Melazzi Francesca Cuomo, Antonio Maurizio, "An on-line spreading factor allocation for a lorawan network", 2019. 44

[83] Aamir Mahmood, Emiliano Sisinni, Lakshmikanth Guntupalli, Raul Rondon, Syed Ali Hassan, and Mikael Gidlund, "Scalability analysis of a lora network under imperfect orthogonality", *IEEE Transactions on Industrial Informatics*, vol. 15, no. 3, pp. 1425–1436, 2019. 44, 78, 109

[84] Francesca Cuomo, Manuel Campo, Alberto Caponi, Giuseppe Bianchi, Giampaolo Rossini, and Patrizio Pisani, "Explora: Extending the performance of lora by suitable spreading factor allocations", IEEE. 45, 109

[85] Domenico Garlisi‡ Ilenia Tinnirello‡ Giuseppe Bianchi†, Francesca Cuomo, "Capture aware sequential waterfilling for lorawan adaptive data rate", 2019. 45

[86] D. Saluja, R. Singh, L. K. Baghel, and S. Kumar, "Scalability analysis of lora network for snr-based sf allocation scheme", *IEEE Transactions on Industrial Informatics*, vol. 17, no. 10, pp. 6709–6719, 2021. 45

[87] P. Kumari, H. P. Gupta, and T. Dutta, "A nodes scheduling approach for effective use of gateway in dense lora networks", in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, pp. 1–6. 45

[88] A. Khalifeh, S. Shraideh, and K. A. Darabkh, "Joint channel and spreading factor selection algorithm for lorawan based networks", in *2020 International Conference on UK-China Emerging Technologies (UCET)*, pp. 1–4. 45

[89] A. Kaburaki, K. Adachi, O. Takyu, M. Ohta, and T. Fujii, "Autonomous decentralized traffic control using q-learning in lpwan", *IEEE Access*, vol. 9, pp. 93651–93661, 2021. 46

[90] Orestis Georgiou, Constantinos Psomas, and Ioannis Krikidis, "Coverage scalability analysis of multi-cell lora networks", IEEE. 46, 110

[91] Martin Haenggi, "Stochastic geometry for wireless networks". 47

[92] T. H. Nguyen, W. S. Jung, L. T. Tu, T. V. Chien, D. Yoo, and S. Ro, "Performance analysis and optimization of the coverage probability in dual hop lora networks with different fading channels", *IEEE Access*, vol. 8, pp. 107087–107102, 2020. 47

[93] Romain Chevillon, Andrieux Guillaume, and Jean-François Diouris, *Coverage of LoRa Links with a-Stable Modeled Interfering Underlying IoT Networks*, 2021. 47

[94] C. Zheng, M. Egan, L. Clavier, G. W. Peters, and J. M. Gorce, "Copula-based interference models for iot wireless networks", in *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, pp. 1–6. 47

[95] U. Coutaud, M. Heusse, and B. Tourancheau, "Adaptive data rate for multiple gateways lorawan networks", in *2020 16th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pp. 1–6. 47

[96] Christia Charilaou, Spyros Lavdas, Ala Khalifeh, Vasos Vassiliou, and Zinon Zinonos, "Firmware update using multiple gateways in lorawan networks", *Sensors*, vol. 21, no. 19, pp. 6488, 2021. 47

[97] LoRa Alliance, "Fuota process summary technical recommendation tr002 v1.0.0", 2021. 48

[98] Yuyi Sun, Jiming Chen, and Shibo He, "High-confidence gateway planning and performance evaluation of a hybrid lora network", *IEEE Internet of Things Journal*, vol. PP, pp. 1–1, 2020. 48

[99] Laurent Chasserat, Nicola Accettura, and Pascal Berthou, "Short: Achieving energy efficiency in dense lorawans through tdma", in *2020 IEEE 21st International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*, 2020, pp. 26–29. 48

[100] C. Gu, R. Tan, X. Lou, and D. Niyato, "One-hop out-of-band control planes for low-power multi-hop wireless networks", in *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*, pp. 1187–1195. 48, 141

[101] Dimitrios Zorbas, Khaled Abdelfadeel, Victor Cionca, Dirk Pesch, and Brendan O'Flynn, *Offline Scheduling Algorithms for Time-Slotted LoRa-based Bulk Data Transmission*, 2019. 50, 53

[102] Thomas Schmid, Zainul Charbiwala, Jonathan Friedman, Young H Cho, and Mani B Srivastava, "Exploiting manufacturing variations for compensating environment-induced clock drift in time synchronization", *ACM SIGMETRICS Performance Evaluation Review*, vol. 36, no. 1, pp. 97–108, 2008. 51, 52

[103] Benoit Ponsard and Juan Carlos Zúñiga, "Sigfox system description", 2017. 51

[104] Joseph Finnegan, Ronan Farrell, and Stephen Brown, "Analysis and enhancement of the lorawan adaptive data rate scheme", *IEEE Internet of Things Journal*, vol. 7, no. 8, pp. 7171–7180, 2020. 51

[105] D. Croce, M. Gucciardo, S. Mangione, G. Santaromita, and I. Tinnirello, "Impact of lora imperfect orthogonality: Analysis of link-level performance. matlab", *IEEE Communications Letters*, vol. 22, no. 4, pp. 796–799, 2018. 53, 70, 76, 146, 151

[106] Martin Haubro, Charalampos Orfanidis, George C. Oikonomou, and Xenofon Fafoutis, "Tsch-over-lora: long range and reliable ipv6 multi-hop networks for the internet of things", *Internet Technology Letters*, vol. 3, 2020. 53, 60, 63

[107] Dinh Loc Mai and Myung Kyun Kim, "Multi-hop lora network protocol with minimized latency", *Energies*, vol. 13, no. 6, pp. 1368, 2020. 53, 60, 63, 65

[108] Anna Triantafyllou, Dimitrios Zorbas, and Panagiotis Sarigiannidis, "Time-slotted lora mac with variable payload support", *Computer Communications*, vol. 193, pp. 146–154, 2022. 53, 54, 60, 63, 64

[109] Hanan Alahmadi, Fatma Bouabdallah, and Ahmed Al-Dubai, "A novel time-slotted lora mac protocol for scalable iot networks", *Future Generation Computer Systems*, vol. 134, pp. 287–302, 2022. 53, 55, 60, 63

[110] FloRa official site., "Flora a discrete event simulator.", 2020. 55, 65

[111] Christian Ebi, Fabian Schaltegger, Andreas Rust, and Frank Blumensaat, "Synchronous lora mesh network to monitor processes in underground infrastructure", *IEEE Access*, vol. 7, pp. 57663–57677, 2019. 60, 63

[112] Dimitrios Zorbas and Xenofon Fafoutis, "Time-slotted lora networks: Design considerations, implementations, and perspectives", *IEEE Internet of Things Magazine*, pp. 1–6, 2020. 69, 145, 172

[113] G. Boquet, P. Tuset-Peiró, F. Adelantado, T. Watteyne, and X. Vilajosana, "Lr-fhss: Overview and performance analysis", *IEEE Communications Magazine*, vol. 59, no. 3, pp. 30–36, 2021. 73, 77

[114] Hamed Hashemi and Ali Hajimiri, "Concurrent multiband low-noise amplifiers-theory, design, and applications", *Microwave Theory and Techniques, IEEE Transactions on*, vol. 50, pp. 288–301, 2002. 73

[115] M. Altayeb, M. Zennaro, E. Pietrosemoli, and P. Manzoni, "Turbolora: Enhancing lorawan data rate via device synchronization", in *2021 IEEE 18th Annual Consumer Communications Networking Conference (CCNC)*, pp. 1–4. 73, 75

[116] Nicholas Sornin et al., "Lora® and lorawan®: A technical overview ,technical paper", 2019. 73

[117] M. C. Dumitru, R. N. Pietraru, and M. A. Moisescu, "Lorawan as open scalable iot ecosystem", in *2023 13th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, pp. 1–6. 74

[118] M. Loriot, A. Aljer, and I. Shahrour, "Analysis of the use of lorawan technology in a large-scale smart city demonstrator", *2017 Sensors Networks Smart and Emerging Technologies (Senset)*, 2017. 75

[119] Frank Loh, Noah Mehling, Stefan Geißler, and Tobias Hoßfeld, "Efficient graph-based gateway placement for large-scale lorawan deployments", *Computer Communications*, vol. 204, pp. 11–23, 2023. 75

[120] Semtech, "An1200.22 lora™ modulation basics available on semtech corporationand lora allaince", 2015. 75, 78, 81

[121] Charles Lehong, Bassey Isong, Francis Lugayizi, and Adnan Abu-Mahfouz, "A spreading factor congestion status-aware adaptive data rate algorithm", *Journal of Sensor and Actuator Networks*, vol. 10, no. 4, pp. 70, 2021. 75

[122] Shie-Yuan Wang, Ji-Jhe Zou, Yo-Ru Chen, Chun-Chia Hsu, Yu-Hsiang Cheng, and Chia-Hung Chang, "Long-term performance studies of a lorawan-based pm2.5 application on campus", in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018, pp. 1–5. 76

[123] I. S. Batalha, A. V. R. Lopes, W. G. Lima, Y. H. S. Barbosa, M. C. A. Neto, F. J. B. Barros, and G. P. S. Cavalcante, "Large-scale modeling and analysis of uplink and downlink channels for lora technology in suburban environments", *IEEE Internet of Things Journal*, pp. 1–1, 2022. 76

[124] Joseph Marin-Alvarez and Juan Lara-Herrera, "Monitoring of marine litter collection device using lorawan on the peruvian coast", in *2020 IEEE International Conference on Engineering Veracruz (ICEV)*, 2020, pp. 1–4. 76

[125] I Kevin, Kai Wang, Shiyang Wu, Ameer Ivoghlian, Zoran Salcic, Andrew Austin, and Xiaokang Zhou, "Lws: A lorawan wireless underground sensor network simulator for agriculture applications", in *2019 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI)*. IEEE, 2019, pp. 475–482. 76

[126] Aamir Mahmood, Emiliano Sisinni, Lakshmikanth Guntupalli, Raúl Rondón, Syed Ali Hassan, and Mikael Gidlund, "Scalability analysis

of a lora network under imperfect orthogonality", *IEEE Transactions on Industrial Informatics*, vol. 15, no. 3, pp. 1425–1436, 2019. 76

[127] Dimitrios Zorbas, Patrick Maille, Brendan O'Flynn, and Christos Douligeris, "Fast and reliable lora-based data transmissions", IEEE. 78

[128] C. Orfanidis, L. M. Feeney, M. Jacobsson, and P. Gunningberg, "Investigating interference between lora and ieee 802.15.4g networks", in *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pp. 1–8. 78

[129] H. Gao, Z. Huang, X. Zhang, and L. Huang, "Design of lora communication protocol for image transmission", in *2023 8th International Conference on Intelligent Computing and Signal Processing (ICSP)*, pp. 2142–2146. 78, 113

[130] T.S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall communications engineering and emerging technologies series. Prentice Hall PTR, 2002. 81, 117

[131] Martin Bor, Utz Roedig, Thiemo Voigt, and Juan Alonso, *Do LoRa Low-Power Wide-Area Networks Scale?*, 2016. 81, 88, 96, 98, 117, 128, 130, 138, 139, 157

[132] Juha Petajajarvi, Marko Pettissalo, Konstantin Mikhaylov, Antti Roivainen, and Tuomo Hänninen, *On the Coverage of LPWANs: Range Evaluation and Channel Attenuation Model for LoRa Technology*, 2015. 81, 117

[133] Mingshu Han, Xiaodong Cheng, Fei Xu, and Jie Zhang, "Study of spds-tdma time slot allocation protocol based on multi-channel communication", *2021 IEEE 2nd International Conference on Big Data, Artificial Intelligence and Internet of Things Engineering (ICBAIE)*, pp. 513–517, 2021. 83

[134] A. Mastilovic, D. Vukobratovic, D. Jakovetic, and D. Bajovic, "Cooperative slotted aloha for massive m2m random access using

directional antennas", in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, pp. 731–736. 107

[135] A. Xanthopoulos, A. Valkanis, G. Beletsioti, G. I. Papadimitriou, and P. Nicopolitidis, "On the use of backoff algorithms in slotted aloha lorawan networks", IEEE. 107

[136] Y. Yang and L. Dai, "Stability region and transmission control of multi-cell aloha networks", *IEEE Transactions on Communications*, vol. 71, no. 9, pp. 5348–5364, 2023. 108, 111

[137] J. Ding, D. Qu, P. Liu, and J. Choi, "Machine learning enabled preamble collision resolution in distributed massive mimo", *IEEE Transactions on Communications*, vol. 69, no. 4, pp. 2317–2330, 2021. 108

[138] Junhee Lee, Wun-Cheol Jeong, and Byeong-Cheol Choi, "A scheduling algorithm for improving scalability of lorawan", IEEE. 109

[139] O. Georgiou and U. Raza, "Low power wide area network analysis: Can lora scale?", *IEEE Wireless Communications Letters*, vol. 6, no. 2, pp. 162–165, 2017. 109

[140] F. Cuomo, M. Campo, E. Bassetti, L. Cartella, F. Sole, and G. Bianchi, "Adaptive mitigation of the air-time pressure in lora multi-gateway architectures", in *European Wireless 2018; 24th European Wireless Conference*, pp. 1–6. 109

[141] Eduardo Sallum, Nuno Pereira, Mário Alves, and Max Santos, "Improving quality-of-service in lora low-power wide-area networks through optimized radio resource management", *Journal of Sensor and Actuator Networks*, vol. 9, no. 1, pp. 10, 2020. 109

[142] Shusuke Narieda, Takeo Fujii, and Kenta Umebayashi, "Energy constrained optimization for spreading factor allocation in lorawan", *Sensors*, vol. 20, no. 16, pp. 4417, 2020. 109

[143] Ali Loubany, Samer Lahoud, and Rida El Chall, "Adaptive algorithm for spreading factor selection in lorawan networks with multiple gateways", *Computer Networks*, vol. 182, pp. 107491, 2020. 109

[144] M. R. Islam, M. Bokhtiar-Al-Zami, B. Paul, R. Palit, J. C. Grégoire, and S. Islam, "Interference issues in lorawan: A comparative study using simulator and analytical model", in *2022 IEEE Region 10 Symposium (TENSYMP)*, pp. 1–6. 109

[145] M. Chen, L. Mokdad, J. Ben-Othman, and J. M. Fourneau, "Dynamic parameter allocation with reinforcement learning for lorawan", *IEEE Internet of Things Journal*, vol. 10, no. 12, pp. 10250–10265, 2023. 109, 111

[146] D. Bankov, E. Khorov, and A. Lyakhov, "Mathematical model of lorawan channel access with capture effect", *2017 Ieee 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (Pimrc)*, 2017. 109

[147] I. El Korbi, Y. Ghamri-Doudane, and L. A. Saidane, "Lorawan analysis under unsaturated traffic, orthogonal and non-orthogonal spreading factor conditions", *2018 Ieee 17th International Symposium on Network Computing and Applications (Nca)*, 2018. 109

[148] A. Loubany, S. Lahoud, A. E. Samhat, and M. E. Helou, "Throughput improvement for lorawan networks considering iot applications priority", in *2023 6th Conference on Cloud and Internet of Things (CIoT)*, pp. 206–210. 109

[149] M. N. Ochoa, M. Maman, and A. Duda, "Spreading factor allocation for lora nodes progressively joining a multi-gateway adaptive network", in *GLOBECOM 2020 - 2020 IEEE Global Communications Conference*, pp. 1–6. 109, 110, 111

[150] R. Marini and G. Cuozzo, "A comparative performance analysis of lorawan in two frequency spectra: Eu868 mhz and 2.4 ghz", in *2023 Joint European Conference on Networks and Communications 6G Summit (EuCNC/6G Summit)*, pp. 1–6. 110

[151] E. Sisinni, A. Depari, P. Bellagente, A. Flammini, I. Silva, T. Flores, and P. Ferrari, "Can adaptive strategies sustain bidirectional lorawan traffic?", in *2023 IEEE International Workshop on Metrology for Industry 4.0 IoT (MetroInd4.0IoT)*, pp. 66–71. 110

[152] Shahzeb Javed and Dimitrios Zorbas, *Downlink Traffic Demand-Based Gateway Activation in LoRaWAN*, 2023. 110

[153] A. Dongare, R. Narayanan, A. Gadre, A. Luong, A. Balanuta, S. Kumar, B. Iannucci, and A. Rowe, "Charm: Exploiting geographical diversity through coherent combining in low-power wide-area networks", in *2018 17th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 60–71. 110

[154] Y. Bouazizi, F. Benkhelifa, and J. McCann, "Spatiotemporal modelling of multi-gateway lora networks with imperfect sf orthogonality", in *GLOBECOM 2020 - 2020 IEEE Global Communications Conference*, pp. 1–7. 110

[155] M. O. Farooq and D. Pesch, "Evaluation of multi-gateway lorawan with different data traffic models", in *2018 IEEE 43rd Conference on Local Computer Networks (LCN)*, pp. 279–282. 112

[156] N. Mehling, F. Loh, S. Raffeck, and T. Hoßfeld, "Studying slot assignment for multi-gateway time scheduled channel access in lorawan", in *2024 IFIP Networking Conference (IFIP Networking)*, pp. 613–619. 112, 113

[157] A. Guitton and M. Kaneko, "Fairness-aware demodulator allocation in lora multi-gateway networks", *IEEE Networking Letters*, pp. 1–1, 2025. 113

[158] Mkrm Almuhaya, Tawfik Al-Hadhrami, Omparakash Kaiwartya, and David J. Brown, "Mbmd-lora scalable lorawan for internet of things: A multi-band multi-data rate approach", in *Advances in Computational Collective Intelligence*, Ngoc-Thanh Nguyen, Bogdan

Franczyk, André Ludwig, Manuel Nunez, Jan Treur, Gottfried Vossen, and Adrianna Kozierkiewicz, Eds. pp. 54–67, Springer Nature Switzerland. 119, 143

[159] Ali Loubany, Samer Lahoud, Abed Ellatif Samhat, and Melhem El Helou, "Joint throughput-energy optimization in multi-gateway lorawan networks", *Telecommun. Syst.*, vol. 84, no. 2, pp. 271–283, Aug. 2023. 130

[160] Lluís Casals, Bernat Mir, Rafael Vidal, and Carles Gomez, "Modeling the energy performance of lorawan", *Sensors*, vol. 17, no. 10, pp. 2364, 2017. 138

[161] D. Todoli-Ferrandis, J. Silvestre-Blanes, V. Sempere-Payá, and S. Santonja-Climent, "Adaptive beacon period configurator for scalable lorawan downlink applications", *IEEE Access*, vol. 11, pp. 83627–83638, 2023. 138

[162] Sonile K. Musonda, Musa Ndiaye, Hastings M. Libati, and Adnan M. Abu-Mahfouz, "Reliability of lorawan communications in mining environments: A survey on challenges and design requirements", *Journal of Sensor and Actuator Networks*, vol. 13, no. 1, pp. 16, 2024. 138

[163] X. Zheng, F. Yu, L. Liu, and H. Ma, "Loradar: An efficient lora channel occupancy acquirer based on cross-channel scanning", *IEEE Transactions on Mobile Computing*, , no. 01, pp. 1–15, 5555. 143

[164] F. Yu, X. Zheng, L. Liu, and H. Ma, "Loradar: An efficient lora channel occupancy acquirer based on cross-channel scanning", in *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*, pp. 540–549. 143

[165] B. Reynders, W. Meert, and S. Pollin, "Range and coexistence analysis of long range unlicensed communication", in *2016 23rd International Conference on Telecommunications (ICT)*, pp. 1–6. 147

[166] Eric Jacobsen, "Understanding and relating eb/no, snr, and other power efficiency metrics", *Accessed: Jan*, vol. 4, pp. 2018, 2012. 148

[167] Semtech, "Sx1272/3/6/7/8: Lora modem designer's guide , available online : www.semtech.com.", 2013. 148

[168] Jorge Ortin, Matteo Cesana, and Alessandro Redondi, "Augmenting lorawan performance with listen before talk", *IEEE Transactions on Wireless Communications*, vol. PP, pp. 1–1, 2019. 151

[169] Pere Tuset-Peiro Borja Martinez Joan Melià-Seguí Thomas Watteyne Ferran Adelantado, Xavier Vilajosana, "Understanding the limits of lorawan", *IEEE Communications Magazine*, 2017. 151

[170] Ciyuan Chen, Junzhou Luo, Dian Shen, Zhuqing Xu, and Runqun Xiong, "Achieving low queueing latency in time-slotted lora networks", in *2024 27th International Conference on Computer Supported Cooperative Work in Design (CSCWD)*. pp. 3237–3242, IEEE. 151

[171] R. Musaloiu-E, C. J. M. Liang, and A. Terzis, "Koala: Ultra-low power data retrieval in wireless sensor networks", in *2008 International Conference on Information Processing in Sensor Networks (ipsn 2008)*, pp. 421–432. 151

[172] M.F. Tariq, M.A. Ali, and Z.A. Khan, "A survey of network simulators", in *2008 International Conference on Computer, Electrical, and Systems Science, and Engineering*. World Academy of Science, Engineering and Technology, 2008, pp. 24–29. 168, 169

[173] A. D'Alconzo, C. Barba, M. Lapegna, and T. Giustiniano, "A survey on network simulators", *State of the Art*, 2009. 169

[174] Celia Garrido-Hidalgo, Jetmir Haxhibeqiri, Bart Moons, Jeroen Hoebeke, Teresa Olivares, F. Javier Ramirez, and Antonio Fernández-Caballero, "Lorawan scheduling: From concept to implementation", *IEEE Internet of Things Journal*, vol. 8, no. 16, pp. 12919–12933, 2021. 171

[175] Pierluigi Locatelli, Pietro Spadaccino, and Francesca Cuomo, "Ruling out iot devices in lorawan", in *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2022, pp. 1–2. 171

[176] Phoebe Edward, Minar El-Aasser, Mohamed Ashour, and Tallal Elshabrawy, "Interleaved chirp spreading lora as a parallel network to enhance lora capacity", *IEEE Internet of Things Journal*, vol. 8, no. 5, pp. 3864–3874, 2021. 172