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BATTERY LIFE OPTIMIZATION IN LORA NETWORKS USING SPREADING FACTOR REALLOCATION

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OTIMIZAÇÃO DA VIDA ÚTIL DA BATERIA EM REDES LORA USANDO REALOCAÇÃO DO FATOR DE ESPALHAMENTO

Ian Henriques de Andrade

Fevereiro/2025

Orientadores: Rodrigo de Souza Couto
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Programa: Engenharia Elétrica

A Internet das Coisas (IoT) está cada vez mais presente em nosso dia a dia. Além de aplicações cotidianas, como automação residencial, as aplicações que atualmente atraem mais atenção são voltadas para uso em larga escala, seja em indústrias, cidades inteligentes ou agricultura. Essas aplicações têm em comum a necessidade de usar redes de comunicação de longo alcance, baixo consumo de energia e baixo custo. Assim, a utilização de Redes de Longo Alcance e Baixo Consumo de Energia (LPWANs) está se tornando mais difundida, uma vez que essas redes possuem as características mencionadas e são vistas como um dos facilitadores da IoT.

Entre as LPWANs, o LoRaWAN tem atraído atenção significativa devido à sua escalabilidade, baixo custo e ao uso de um espectro não licenciado. O *Adaptative Data Rate* (ADR) é um recurso chave do protocolo LoRaWAN, projetado para otimizar o desempenho e a eficiência de energia dos dispositivos finais (EDs) ajustando seus parâmetros de transmissão, como *Spreading Factor* (SF) e potência de transmissão, com base nas condições da rede, como o RSSI e o SNR, sendo ambos os mais afetados pela distância ao gateway. Esse ajuste dinâmico ajuda a minimizar o consumo de energia dos EDs e a aumentar a capacidade da rede. No entanto, o ADR otimiza a taxa de dados dos EDs individualmente, sem considerar a alocação geral de SF na rede, realizando a alocação de muitos dispositivos para o menor SF possível, o que causa a utilização do mesmo SF por vários EDs, tornando as transmissões suscetíveis a colisões, comprometendo assim a diversidade de rádio e reduzindo a taxa de transmissões de pacotes bem-sucedidas (DER).

Esta dissertação propõe uma estratégia dinâmica para a alocação de recursos utilizados pelos dispositivos finais no LoRaWAN. A estratégia proposta de otimização da vida útil da bateria (BLO) divide os dispositivos finais em diferentes grupos de *Spreading Factor*

(SF). A ideia básica é reduzir as colisões entre dispositivos finais que utilizam o mesmo SF. Além disso, o BLO também considera o nível atual da bateria de cada dispositivo final e, periodicamente, realoca os grupos de SF para otimizar o consumo de bateria de todos os nós e estender a vida útil da rede. A principal inovação do BLO é considerar, além do RSSI, o tempo de ar para diferentes SFs como um fator de ponderação na alocação de SF. Comparamos o BLO às estratégias de alocação de SF que são estado da arte na bibliografia, alcançando uma melhoria de 55% na entrega bem-sucedida de mensagens em comparação com o esquema ADR do LoRaWAN. Além disso, obtemos melhor eficiência energética com o BLO. Em um cenário com um gateway e 500 dispositivos operando por 24 horas, a mínima bateria remanescente dentre os dispositivos da rede com o BLO é 10 e 3.6 vezes maior do que com as estratégias EXPLoRa-SF e EXPLoRa-AT, respectivamente.

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BATTERY LIFE OPTIMIZATION IN LORA NETWORKS USING SPREADING FACTOR REALLOCATION

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The Internet of Things (IoT) is increasingly present in our daily lives. In addition to everyday applications such as home automation, the applications that currently attract the most attention are for large-scale use, whether in industries, smart cities, or agriculture. These applications have in common the need to use long-range, low energy consumption, and low-cost communication networks. Thus, the utilization of Low Power Wide Area Networks (LPWANs) is becoming more widespread, as these networks possess the mentioned characteristics and are seen as one of the enablers for IoT.

Among LPWANs, LoRaWAN has attracted significant attention due to its scalability, low-cost radio modules, and the use of an unlicensed spectrum. Adaptive Data Rate (ADR) is a key feature of the LoRaWAN protocol, designed to optimize the performance and power efficiency of end-devices (ED) by adjusting their transmission parameters, such as spreading factor (SF) and transmission power based on network conditions, such as the RSSI and SNR. Both conditions are mostly affected by the distance to the gateway. This dynamic adjustment helps in minimizing power consumption of EDs and enhance network capacity. However, the ADR scheme optimize the ED's data rate individually without considering the overall SF allocation in the network, performing the allocation of many devices to the lowest SF possible. This causes several EDs using the same SF which makes transmissions susceptible to collisions, thereby compromising radio diversity and reducing the data extraction rate (DER).

This dissertation proposes a dynamic strategy for the allocation of resources used by end devices in LoRaWAN. The proposed battery life optimization (BLO) strategy splits end devices into different spreading factor (SF) groups. The basic idea is to reduce the collisions between end devices using the same SF. Moreover, BLO also considers the current

battery level of each end device, and periodically reallocates the SF groups to optimize the battery consumption of all nodes and extend the network lifetime. The main innovation of BLO is to consider, in addition to the RSSI, the air time of different SFs as a weighting factor in SF allocation. We compare BLO to state-of-the-art (SoA) SF-allocation strategies, achieving 55% improvement in successful message delivery compared to LoRaWAN's ADR scheme. Furthermore, we obtain better energy efficiency with BLO. In a scenario with one gateway and 500 devices operating over 24 hours, the remaining energy with BLO is 10 and 3.6 times larger than with EXPLoRa-SF and EXPLoRa-AT SoA strategies, respectively.

Contents

List of Figures

List of Tables

List of Abbreviations

ADC *Analog-to-Digital Converter*

ADR *Adaptative Data Rate*

AT *Air Time*

BLO *Battery Life Optimization*

BW *Bandwidth*

CSS *Chirp Spread Spectrum*

DER *Data Extraction Rate*

DR *Data Rate*

ED *End Device*

EXPLoRa *Extending the performance of LoRa algorithm*

GW *Gateway*

IC *Integrated Circuits*

IoT *Internet of Things*

ISM *Industrial, Scientific, and Medical*

LPWAN *Low Power Wide Area Networks*

LTE-M *Long Term Evolution for Machines*

MAC *Medium Access Control*

MCU *Microcontroller Unit*

MILP *Mixed Integer Linear Problem*

NB-IoT *Narrowband-IoT*

NS *Network Server*

PPK2 *Power Profiler Kit II*

RSSI *Received Signal Strength Indicator*

SF *Spreading Factor*

SiP *System-in-Package*

SNR *Signal-to-Noise Ratio*

SoA *State-of-the-Art*

SoC *System-On-Chip*

Chapter 1

Introduction

The Internet of Things (IoT) is a well-known concept used to refer to the interconnection of different objects on the Internet, making them capable of transmitting and/or receiving data. Even though it is a well-known concept, its adoption is still in development and continues to attract more and more investments and solutions for new and traditional applications. In residential settings, IoT applications include smart home devices such as thermostats, lighting systems, and security cameras that can be remotely controlled and monitored via mobile apps. In industrial contexts, IoT facilitates smart manufacturing and predictive maintenance by connecting machinery and equipment to the cloud, allowing real-time monitoring of performance and condition, and also optimizing inventory tracking. Regarding smart cities, we can highlight as key implementations the smart public transportation systems, with end device tracking , that optimize traffic flow and public transit, smart lighting, real-time air quality monitoring and water management, improving public health and resource conservation [7].

Since its beginning, some IoT characteristics have been defined as essential for its diffusion, such as the low energy consumption of devices. Long transmission range is also important, to make large-scale deployment feasible in remote locations or broader areas such as cities and industries [8].

The demand for specialized technologies becomes even more crucial when we consider the inherent requirements of IoT projects alongside the need for wireless communication over significant ranges of applications such as security, motion control, agriculture, smart measurement, smart cities, and smart homes. Short-range technologies such as Bluetooth, Wi-Fi and Zigbee are not the best fit, while cellular communication technologies (3G, 4G, and 5G) offer broader coverage but often come with high power consumption. These essential needs in IoT have driven the development and adoption of several Low Power Wide Area Networks (LPWAN) technologies.

As mentioned, the extended battery life of Internet of Things (IoT) devices is crucial to ensuring reliability and availability, especially in remote locations where maintenance is difficult [9]. With longer battery life, maintenance and operating costs decrease, making solutions more economical in the long term and contributing to sustainability by reducing electronic waste. Furthermore, devices with greater autonomy allow the exploration of new applications, improving interoperability in connected networks and providing a superior user experience for consumers. This drive for energy efficiency and long-lasting batteries has also driven technological innovation, spurring advances in battery chemistry and device design, which ultimately contributes to a more connected and sustainable future. Another area of research to increase the autonomy of end devices is the use of energy harvesting, that involves capturing and storing energy from environmental sources like solar, thermal, vibration, RF, and wind energy. An already explored area to save energy from devices is to reduce the radio consumption, proposing new technologies or improvements of the existing one, that will be the focus in this work.

Long-range communications play a crucial role in the successful implementation of Internet of Things (IoT) solutions, particularly in scenarios requiring wide coverage and the ability to connect numerous devices over significant distances, e.g., agriculture and smart cities [10]. Furthermore, long-range communications enhance scalability and flexibility in IoT deployments, allowing for the integration of more sensors and devices without the need for extensive additional infrastructure, reducing significantly the cost to implement the mentioned applications.

Another requirement for Internet of Things (IoT) that is crucial for widespread adoption and scalability of IoT solutions is the low-cost of the end devices and also of the network [11]. As businesses and consumers wants to integrate smart technologies into their operations and daily lives, the price becomes a key barrier to entry. Low-cost devices enable more extensive deployment across various applications, from smart agriculture to home automation, making it feasible for even small business and individual application. For example, in an smart industry application it might be needed to locate tools as hammers or drills, that are cheap gadgets, so if the solution for this is expensive it might be unfeasible. Moreover, reducing device costs encourages innovation, as developers can experiment with novel applications without facing significant financial risks. This democratization of technology not only drives market growth but also accelerates the collection of valuable data, ultimately leading to improved decision-making and operational efficiency across industries. Therefore, achieving cost-effective end devices is essential for unlocking the full potential of IoT and ensuring its long-term success.

To effectively develop an IoT application, a robust network infrastructure is essential to meet the diverse needs of connected devices. These networks must ensure high reliability and a central platform to manage the devices. Scalability is also a critical requirement, as the number of connected sensors and devices can grow exponentially, necessitating a network that handle large volumes of data traffic without compromising the performance [12].

For several applications, especially the ones that needs to be developed in remote areas like agriculture or industries located away from city centers, may be necessary to develop its own private network infrastructure. Networks operating on Industrial, Scientific, and Medical (ISM) bands, such as LoRa, Sigfox and Zigbee, offer significant advantages in this regard. ISM bands are typically unlicensed spectrum, allowing for easier access and deployment without the need for complex regulatory approvals or licensing fees. This facilitates faster time-to-market and cost savings for IoT solutions. Moreover, devices using ISM bands can often be configured to comply with local regulations concerning emissions and interference, promoting an easier integration process across different regions and providing the flexibility needed to scale IoT solutions globally.

A secure infrastructure is also critical for the development of IoT [13]. In applications like surveillance and monitoring, it is essential to ensure that each device is properly identified and its data is protected. However, the extensive interconnection of devices in IoT networks creates a significant security risk. Existing security measures for traditional networks are often insufficient for IoT, as the number of devices and connections makes it difficult to implement and maintain robust security protocols. Therefore, several LPWANs develop their own security measures with the objective to attend this needs.

For time-sensitive applications (e.g., industrial automation, healthcare monitoring and smoke alarm), low latency is crucial. Therefore, when selecting an LPWAN for a specific application, it is crucial to carefully evaluate the latency requirements and determine if the network can meet the applications needs without compromising performance.

Over the last decade, different wireless networks classified as "Low Power Wide Area Networks" (LPWANs) emerged to fulfill the needs of IoT solutions [14], designed to facilitate communication between devices even in remote or challenging environments, where traditional networks may be inadequate. LPWANs, besides the aforementioned aspects, are also characterized by low data rates, small packet sizes, a large number of connected devices, and simple network topologies.

LPWAN technologies appear to enable several applications that requires long range communication in battery-powered small devices, that needs low power consumption to increase its useful life time. In this dissertation, we overview four technologies, Sigfox, LoRa, NB-IoT, and LTE-M aiming to find the most suitable for the future of Internet of Things (IoT). Among the main characteristics presented of each network, we highlight the standartization, operation's frequency in Brazil, Bandwidth, data rate, maximum payload size, and maximum transmission range.

The overview of LPWANs provided in this dissertation demonstrates that no single technology can meet the diverse requirements of all IoT applications. As will be presented, each LPWAN technology has its strengths and weaknesses. Therefore, the decision on which technology to use depends on various factors, including the specific application, the device's location, mobility, latency, and the required data rate, among others. In vending machines, in which payment data is transmitted to servers to authenticate, LTE-M is a more suitable choice than others because of its low latency, but NB-IoT can be also an alternative to be considered. In agriculture, where data about soil humidity and temperature indicators are transmitted, Sigfox and LoRaWAN are more suitable technologies because of their cost-efficiency, low bandwidth usage, and lower power consumption.

Among LPWANs, LoRa (Long Range) has attracted major attention [15] [16] due to its scalability [17], low cost radio modules and the usage of an unlicensed spectrum, allowing the implementation of private networks anywhere. The LoRa technology was developed by Semtech, which is the patent holder for the employed modulation. The LoRa Alliance[1] on the other hand is a non-profit organization composed of more than 500 member companies which actively develop the LoRaWAN open standard. LoRa, which is physical layer technology, employs a Chirp Spread Spectrum (CSS) type modulation [18]. In CSS, each bit of data is represented by multiple information symbols according to the chosen Spreading Factor (SF). On the other hand, LoRaWAN is a standardized bidirectional messaging protocol of the Medium Access Layer (MAC) over LoRa modulation. LoRaWAN is responsible for managing topology, channels, data rates, and MAC commands.

The LoRaWAN network defines a star-of-stars topology in which gateways relay messages between end devices and a central network server. Gateways serve as the essential link between LoRaWAN end devices (sensors, actuators, etc.) and the network server (NS). They enhance coverage, ensure redundancy, handle multiple channels and data rates, and support network management. Gateways are connected to the NS using a backhaul (e.g., cellular, Ethernet, satellite, or Wi-Fi).The NS is responsible for decrypting the packet, removing duplicates if the packet was received by more than one gateway, and forwarding the data to the corresponding applications.

LoRaWAN operates in various frequency bands depending on the region (e.g., 868 MHz in Europe, 915 MHz in the US) [5]. Within these bands, LoRaWAN uses a set of predefined channels. In addition to random transmissions across these channels, end devices use a variable Data Rate (DR) setting. The DR is determined by the bandwidth (BW) and the Spreading Factor (SF) used. SF selection allows a dynamic trade-off between communication range and the transmission's Air Time (AT), which refers to the amount of time a radio signal is actively being transmitted from a device, that's is directly related to power consumption. By using a lower SF, the transmission will have a shorter range, but the Air Time is also reduced, consuming less battery and opening up more potential space for other nodes to transmit. Additionally, the SFs are orthogonal, so that signals modulated with different spreading factors and transmitted on the same frequency channel at the same time do not interfere with each other, increasing network's capacity.

To maximize the battery life of end devices, the LoRaWAN Network Server (NS) manages the DR setting and RF output power for each end device individually through the Adaptive Data Rate (ADR) scheme [19]. The ADR is the default mechanism for optimizing the SF selection, bandwidth, and power transmission individually for each end device,

[1] https://lora-alliance.org/

to optimize device power consumption while ensuring that messages are still received at the Gateways (GWs). To determine the optimal data rate, the network needs some measurements (i.e., a few uplink messages). These measurements contain the frame counter, signal-to-noise ratio (SNR), and the number of GWs that received each uplink message. For each of these measurements, the ADR takes the SNR of the best gateway, and computes the optimal data rate. It is important to mention that this choice is made to achieve the lowest power consumption possible and it does not take into consideration the network's health, such as the Data Extraction Rate (DER) or SF congestion (i.e., many nodes using the same SF) and the network throughput. We define the DER as in [20], i.e., the ratio of received packets by the GWs to transmitted packets from all the network EDs, over a period of time.

Lately, some studies have started to evaluate the performance of LoRaWAN networks, targeting to improve aspects such as scalability and performance limits. The focus of some works is a more efficient SF allocation scheme for the end devices [21] [22] [23]. Again, the ADR mechanism does not consider the overall performance of the network for SF allocation. Therefore, taking advantage of SF's orthogonality, it is possible to develop a mechanism to reduce interference among groups of devices which are assigned to different SFs, and therefore improve network capacity.

This dissertation proposes a new mechanism to allocate spreading factors periodically, called Battery Life Optimization (BLO). BLO leverages the concept of splitting end devices into SF groups, to reduce the collisions in larger groups using the same SF, improving the network performance. The major difference in the BLO, as compared to the literature, is that it takes into account the current battery level of the end device to schedule a periodic reallocation of SF groups to optimize, in a fair way, the battery life of all nodes in the network. To evaluate the performance of BLO, we conduct experimental measurements of LoRa transmission power consumption, differently from most work which is based only on simulations or mathematical models [24].

This study further develops a method to solve the optimization problem of allocating an appropriate spreading factor to EDs as a mixed-integer linear program (MILP). BLO is effective especially at high traffic loads, when there are hundreds or thousands of nodes transmitting in an area. Simulations reveal that BLO outperforms other proposals, achieving a remarkable 55% increase in successful message delivery rates when compared to LoRaWAN's Adaptive Data Rate (ADR) scheme. Furthermore, we observe significant increase in network lifetime comparing BLO with state-of-the-art (SoA) strategies, with improvements of 10 and 3.6 times over EXPLoRa-SF and EXPLoRa-AT, respectively, in a network with 500 devices served by one LoRa GW.

Regarding the motivation for this dissertation, numerous applications involves the requirements of a high frequency of packet transmissions, low power consumption (for battery-powered devices) and need to have considerable data delivery reliability, with a higher Data Extraction Rate. One example is the connected worker application [25] [26], that refers to the use of IoT technologies to enhance worker productivity, safety, and efficiency in various industries. In industries that have a high risk of accidents, wearable devices can monitor vital signs and environmental conditions (e.g., temperature, gases) to alert workers and management of potential hazards. This application can enable real-time tracking of worker activities, increasing safety. Therefore, an application such as this one has the need to support several devices (e.g., for monitoring hundreds of workers in the factory floor). Depending on the risks in the industry, the location information of the worker might be needed with low intervals, such as 1 minute. Furthermore, for these type of applications it is necessary to have low packet collision so that important information, such as an employee entering an area where a gas alarm has sounded, is not lost. However, through this dissertation, a holistic view regarding the large range of possible applications is maintained, where there is a need for constant transmission, with lowest consumption possible, high scalability and high data delivery reliability. Therefore, these parameters are the one's that will have more attention when comparing the proposed improvement on SF allocation on LoRaWAN networks.

The primary contribution of this dissertation is the proposal of a novel dynamic spreading factor (SF) allocation scheme for LoRaWAN networks aimed at improving network scalability, particularly in high-traffic scenarios. This scheme also seeks to improve fairness in battery consumption among end devices (EDs) by incorporating the current battery percentage into the SF allocation algorithm. Additionally, this dissertation makes significant contributions to the understanding of power consumption in LoRaWAN by providing measured data on the energy consumption of a LoRaWAN end device.

This dissertation is organized as follows. Chapter 2 provides an overview of key topics addressed in this dissertation, focusing on Low Power Wide Area Networks (LPWAN). This chapter includes a summary and comparison of the current leading networks in this domain, as well as a detailed discussion of the LoRaWAN protocol and important concepts such as air time. Chapter 3 presents the main works in the current literature. Chapter 4 presents some experimental contributions on LoRaWAN's energy consumption, using a state-of-art power monitoring equipment, designed for measuring low-power devices. Chapter 5 presents the BLO proposal and the related optimization problem. Chapter 6 shows the performance analysis using the NS-3 simulator. This chapter also provides and a explanation about the network simulation tool used in this dissertation (NS-3). Chapter 7 concludes the paper and outlines potential directions for future research.

Chapter 2

Background

This chapter provides an overview of the main concepts used in this dissertation. The following sections outline key theoretical foundations and technical aspects that are essential to understanding the development and methodology employed.

2.1 Low Power Wide Area Networks

In the past decade, various communication networks classified as Low Power Wide Area Networks (LPWANs) have emerged to facilitate the implementation of Internet of Things (IoT) solutions. As illustrated in Figure 2.1, LPWANs are characterized by their long-range capabilities, low energy consumption, and low data transmission rates. This low throughput is not necessarily an issue, given that the many IoT applications require only a few bytes to transmit their data, while extended range and battery life are paramount.

In [27] and [28] the main characteristics that allowed the dissemination of LPWANs are presented:

- **Long range** – This allows devices to transmit data to gateways even if they are miles away.

- **Low data rates** – Most applications consume few bytes (or bits) of data, such as a trash bin sensor, which can send a '0' bit when it is not full and a '1' bit when it reaches a determined limit.

- **Low power consumption** – In addition to these technologies being optimized for this purpose, they also consider that the recurrence of data transmission is very low, with sensors that can transmit one packet per day or week, for example.

- **Low cost** – As these devices do not need to have very high computational power, this makes the hardware cheaper. Several SiP's (*System-in-Package*) are already available on the market, including boards with a simple micro-controller and a radio interface within an integrated circuit. Among these commercial Integrated Circuits (IC),

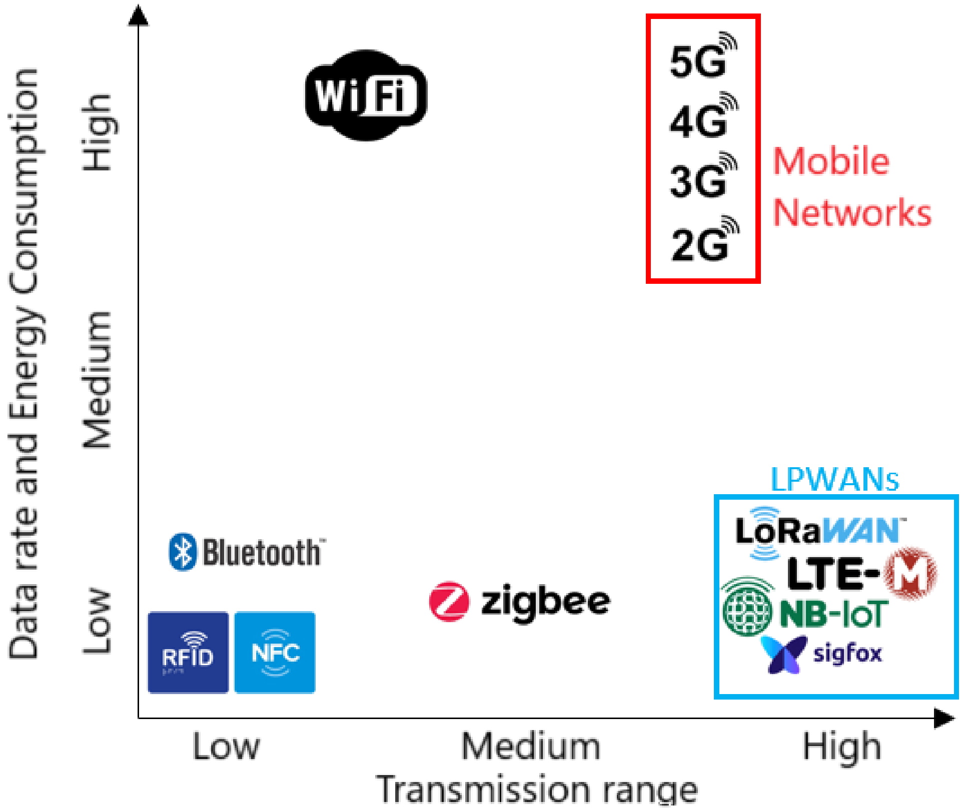


Figure 2.1: LPWANs vs. other wireless network technologies.

we can mention the S76G/S SiP from AcSiP[29], the STM32WLE System-On-Chip (SoC) from STMicroelectronics[30], and the LSM100A module from SJIT [31]. The first two operate with LoRa technology, and the last one supports both LoRa and Sigfox.

- **Large number of connected devices** – LPWANs allow thousands of devices to connect to a single antenna. This is possible because the transmission duty cycle of the devices is very small and they use technologies that seek to avoid packet collisions.

- **Use of unlicensed spectrum** – Some LPWANs use free ISM (Industrial, Scientific, and Medical) band spectrum (LoRa, for example) and therefore do not need to pay for licensing, reducing the cost of deployment.

- **Simplified network topology** – Most LPWANs use a star topology (rather than the mesh or tree topologies used in other technologies), in which devices communicate directly with a base station. This characteristic is also another reason for the low power consumption of the end devices (ED), because they don't need to perform routing or any other function on the network, just send data and receive commands.

There are various potential applications for LPWANs. Also in [27], several of these

Table 2.1: LPWANs applications and it's requirements

Application	**Data rate**	**Mobility**	**Real time requirement**	**Suggested LPWAN**
Vehicle tracking	Depends	Yes	Depends	LoRaWAN
River monitoring	Low-Medium	No	No	LoRaWAN / Sigfox
Agriculture	Low	No	No	LoRaWAN / Sigfox
Health	Medium	Depends	Yes	NB-IoT / LTE-M
Smart industry	High	No	Yes	LTE-M
Smart cities	Low-Medium	Depends	Depends	LoRaWAN / Sigfox

applications are presented, along with an explanation of their different requirements. This differentiation enables certain LPWANs to be more suitable for specific applications. Table 2.1 lists examples of applications along with their respective requirements and the more suitable LPWANs. Some applications have flexible requirements based on the specific use case, e.g. vehicle tracking that can have variable data rate requirements. In applications where a vehicle must trigger an alert when it enters or exits a predefined geographic area (geofencing), the data transmission may only be necessary when the vehicle crosses these boundaries. Nonetheless, in scenarios where the vehicle's precise location needs to be updated frequently (e.g., police car), the data rate requirement would be higher.

In [32] the main LPWAN technologies currently used are presented: LoRaWAN, Sigfox, NB-IoT (Narrowband-IoT) and LTE-M (Long Term Evolution for Machines). Furthermore, the basic functioning of each of these networks is shown, presenting the physical layer and the medium access layer (MAC) of each technology.

In this section, we provide an overview of the most widely used Low Power Wide Area Networks (LPWANs) according to [32] , highlighting their advantages and disadvantages, as well as presents various applications documented in the literature. To conclude, we make a brief comparative analysis of these networks.

2.1.1 LoRaWAN

LoRa was developed by Semtech, which holds the patent for this modulation, and founded the LoRa Alliance, a nonprofit association made up of over 500 member companies that actively develop the open LoRaWAN® standard. LoRa (Long Range) is a Chirp Spread Spectrum (CSS) modulation technique where each bit of information is represented by multiple information symbols, according to the chosen Spreading Factor (SF). The detailed informations about CSS modulation is described in [33].

CSS modulation involves the use of chirps, which are frequency modulated signals that traverse a bandwidth [**?**]. Chirp Spread Spectrum (CSS) has the advantage of being resilient to interference and multipath fading, making it suitable for IoT applications requiring reliable communication over long distances with low energy consumption. Nonetheless, CSS has the drawback of limited data rates and spectral inefficiency.

LoRaWAN is a standardized bi-directional messaging protocol based on LoRa modulation. The LoRaWAN protocol stack consists of three primary layers: the physical layer, the MAC layer, and the application layer, as shown in Figure 2.2. LoRaWAN is responsible for the MAC layer, managing the topology, channels, data rates, and MAC commands while LoRa modulation handles the physical layer.

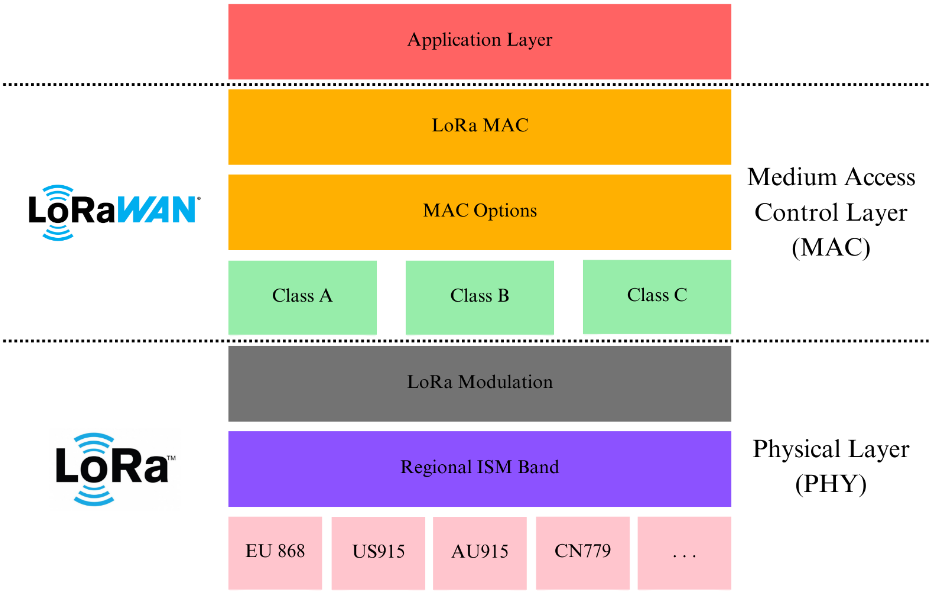


Figure 2.2: LoRaWAN protocol stack (adapted from [1]) .

In [34], the characteristics of LoRaWAN are presented in a simplified manner. The network structure can be separated into Back-End and Front-End. The Front-End uses a star network topology and consists of gateways and end devices, which do not have routing capabilities and send their messages directly to the gateways through a one-hop mechanism. The gateway acts as a bridge between the end devices and the Network Server, which is part of the Back-End. The Network Server is responsible for removing duplicates (in case the packet has been received by more than one gateway), verifying whether the received packet is from a registered device (if not, the packet is discarded), and directing it to the Application Server, which is responsible for decrypting the packet and forwarding the data to the applications. The basic LoRaWAN topology is shown in Figure 2.3.

The LoRaWAN protocol employs a multi-layered security architecture designed to provide data integrity and protect user privacy throughout the communication process. Security in LoRaWAN is primarily based on two main techniques: end-to-end encryption and the use of unique device identifiers. Each LoRaWAN device is configured with a unique AES-128 symmetric key (called AppKey) and a globally unique identifier (EUI-64-based DevEUI), both of which are used during the device authentication process [35]. Two session-specific encryption keys are then derived from the AppKey: each device in

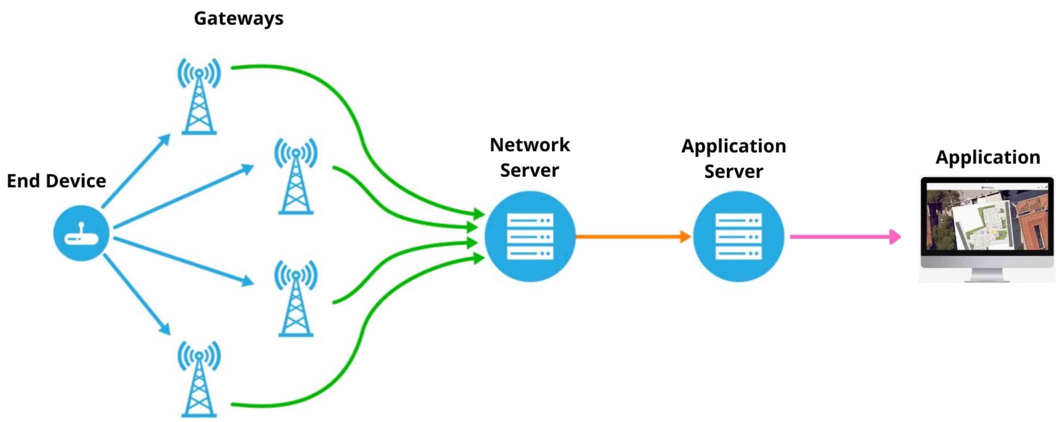


Figure 2.3: Basic LoRaWAN topology (adapted from [2]).

the LoRaWAN network is assigned a unique Network Session Key (NwkSKey) and Application Session Key (AppSKey), ensuring that information is secure from unauthorized access during transmission. Additionally, the network utilizes a secure join process for device authentication, request the proof that both the end device and the network have the knowledge of the AppKey, mitigating risks associated with spoofing and impersonation.

To optimize battery usage and also to make the data transmission rate more flexible, the Adaptive Data Rate (ADR) mechanism was created. It is operated by the Network Server according to certain parameters, such as the reception power of each device, and informs the end device which Data Rate (DR) it should use, allowing for a trade-off between transmission range and transmission duration. Different spreading factors create signals that are orthogonal to each other. This means that when multiple devices transmit at the same frequency but use different spreading factors, they do not interfere with each other, increasing the network capacity. Table 2.2 shows the relationship between Data-Rate (DR), SF, bit rate, reception sensitivity (considering the bandwidth fixed at 125 kHz), air time (considering a 51-byte packet), transmission range, and consumption [5]. The air time and energy consumption values are based on experimental measurements presented on section 4.2. Briefly, the lower the SF, the higher the bit rate and lower the range and consumption, as the radio spends less time to transmit the same number of bytes.

Furthermore, LoRaWAN allows the configuration of end devices into three types of classes, all of them enabling bidirectional communications. Although end devices can send uplink messages at will, the class determines when the end device can receive downlink messages (i.e., packets coming from network to the ED). The class also affects the energy efficiency of a device and consequently its battery life [36]. Next, we detail each

Table 2.2: LoRaWAN:Spreading Factor(SF) vs some parameters.

DR	SF	Bit rate/s	Reception sensibility	Air time (ms)	Range	Energy consumption (µAh/packet)
5	7	5,470	-123 dBm	118.00	Lower	3.28
4	8	3,125	-126 dBm	215.56	.	5.99
3	9	1,760	-129 dBm	390.17	.	10.84
2	10	980	-132 dBm	698.42	.	19.40
1	11	440	-134 dBm	1560.72	.	43.35
0	12	250	-137 dBm	2793.75	Higher	77.60

LoRaWAN class.

- **Class A:** Communication is always initiated by the device and is completely asynchronous, meaning that the device can transmit a packet whenever it wants (ALOHA Protocol). After each transmission, the device opens two reception windows (RX1 and RX2) to receive an ACK or a downlink message, as shown in Figure 2.4. Therefore, the device has the higher energy efficiency since it does not need to be listening to the medium access all the time [37]. Class A is the most widely used among the three classes and must be supported by all devices.

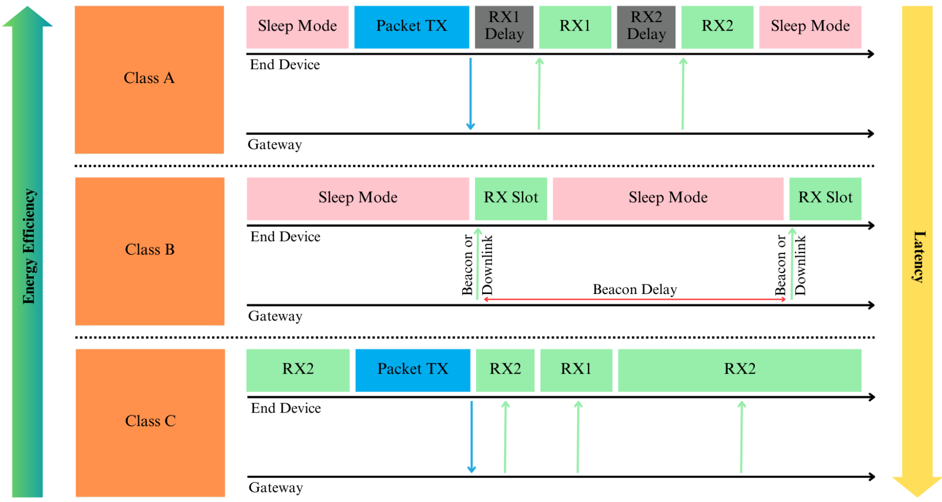


Figure 2.4: Temporal diagram of LoRaWAN Classes (adapted from [3]).

- **Class B:** Besides the identical functioning of class A (opening two reception windows after a transmission), it has scheduled receive windows that allow more frequent downlink communication from the network to the end devices, in comparison to Class A [37].

- **Class C:** C-Class devices keep the reception window always open when not transmitting (Half-Duplex), meaning it is possible to receive a message at any time. This mode has the highest energy consumption (≈50 mW while listening), but with the lowest latency. It is ideal for devices that have a permanent external power supply. It is possible to transition between classes A and C, and one of the use cases could be remote firmware updates (Over-The-Air Update).

Figure 2.5 shows the comparison of LoRaWAN classes regarding the energy efficiency and the latency in the downlink, as well as suggesting applications for each of the classes.

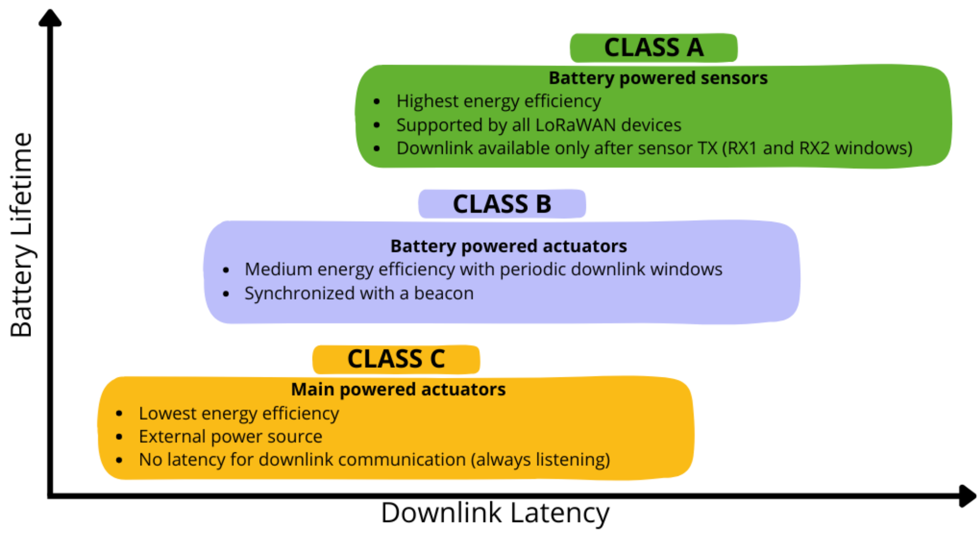


Figure 2.5: LoRaWAN Classes comparison and applications.

The LoRaWAN network is characterized by using the unlicensed ISM frequency band and adopting an open communication protocol, allowing the implementation of private networks as well as the use of public networks. In this way, LoRaWAN stands out for being the only one of the four networks addressed in this section that allows the creation of a private infrastructure independently. It is possible to install your own infrastructure on a farm or industry, for example. Despite this possibility, public networks can be used for most applications. For example, in Brazil there are several operators which sell data plans for to connect LoRa devices for a few Reais a month, such as American Tower [38].

Currently, there is already a large amount of studies and commercial IoT applications using LoRaWAN [39]. In [40], the feasibility of the LoRa network was evaluated for the case of monitoring vital data of individuals in closed environments, such as hospitals. A private infrastructure was created within a university, with only one gateway positioned 24 m high. A delivery rate of 96.7% was achieved, without using acknowledgments (ACK) or retransmissions. In [41], an outdoor geolocation system was created based on the Time

Difference of Arrival (TDoA) technique using a public LoRa network in the Netherlands. An average location error of 200 m was obtained for tests with the user walking, cycling, and also driving.

2.1.2 Sigfox

The Sigfox network was created in France in 2010. It also uses a star topology. One of the differences compared to LoRaWAN is on network management, which is handled directly by Sigfox company itself; that is, it is not possible to create a private network with this technology. It is currently present in more than 70 countries through its own integrators [42]. In terms of the physical layer, Sigfox uses Differential Binary Phase Shift Keying (D-BPSK) modulation and transmits data using a Ultra Narrow Band with 100 Hz channels, which allows for high immunity to noise, low energy consumption, and high reception sensitivity.

SigFox also supports bidirectional communication (UpLink - UL and DownLink - DL), but it is limited to 140 UL packets per day and 4 DL packets per day. Thus, it is clear that it is not possible, for example, to have acknowledgments for all messages [43]. Therefore, to to maximize the probability of message delivery, Sigfox employs a random access method for transmissions and sends the same packet three times on three different frequencies [44].

The maximum transmission rate is 100 bps. Furthermore, the size of UL messages is limited to a payload of 12 bytes of data, with an additional 14 bytes of header, totaling a frame of a maximum of 26 bytes. For DL messages, the maximum allowed is 8 bytes of data [44].

In [45], the use of Sigfox technology was evaluated for monitoring activities within homes for elderly people in Singapore. Door sensors and presence sensors were used to transmit data through the SigFox network. Experiments have shown that there is already coverage of about 95% of the territory in Singapore. A comparison was made with another wireless technology, called Z-wave [46], which requires the installation of a local gateway and is widely used in smart homes. It was found that the battery consumption between them was similar; however, a positive point is that Sigfox does not require the installation of local infrastructure.

In [47], a device location system was evaluated using the fingerprinting technique, utilizing the RSSI from SigFox communication. The fingerprinting technique is based on two stages: an offline stage, in which RSSI data is collected at known points, and an online stage, where it is possible to estimate the position based on this database. The kNN (k Nearest Neighbors) algorithm was used, and 31 different distance functions were evaluated, resulting in an average location error of 340 meters.

2.1.3 NB-IoT

NB-IoT was standardized by 3GPP in 2016. Unlike the two previous LPWAN technologies, NB-IoT does not have a patent on its physical layer, allowing various companies such as Huawei, Ericsson, and Qualcomm to develop their ICs. Furthermore, NB-IoT operates on a licensed LTE/4G or GSM frequency already used by telecommunications operators, requiring only a firmware update on the base stations, enabling up to $100,000$ devices to connect to a single antenna with a range of about 1 km in urban areas and 10 km in rural areas [43]. It utilizes various features of LTE/4G, such as its back-end, adapting them to the needs of an LPWAN.

In [43], a brief summary of the characteristics of NB-IoT is provided. The transmission rate is 200 kbps for UL communication and 20 kbps for DL communication. The maximum message size is 1600 bytes. Regarding modulation, SC-FDMA (Single Carrier Frequency Division Multiple Access) is used for UL and Orthogonal FDMA for DL transmissions. NB-IoT uses a total bandwidth of 200 kHz.

NB-IoT was designed for sporadic transmissions of small packets and is recommended for fixed objects. To initiate a communication with a cell (or base station), there is an authentication step, and if this device moves out of the range of that cell, it is necessary to redo this authentication step with another cell. This can be a problem for mobile applications such as tracking. In addition, this step consumes a lot of energy [48].

In [49], the performance and cost of a smart industry solution using NB-IoT communication were evaluated. The studied use cases included a smart screwdriver, predictive maintenance, inventory management, among others. Regarding performance, it was found that the delay of a 20-byte packet averaged 182 ms, while a 1000-byte packet had a delay of 893 ms, and no packet losses were detected. Additionally, it was estimated that the hardware cost to make a device "smart" with this solution was between 40 and 80 USD, and the estimated cost of the contracted packet operator was 1.50 USD annually per device.

2.1.4 LTE-M

LTE-M was also developed by 3GPP and shares some characteristics with NB-IoT, such as having no patent on its physical layer and using the licensed frequency of LTE/4G or GSM, therefore only a firmware update of the available antennas is needed for them to support this protocol. It uses a total bandwidth of 200 kHz.

LTE-M has a medium access method similar to LTE, which allows both to share the spectrum efficiently. Additionally, LTE-M also features a cell-level authentication step, similar to NB-IoT. Nevertheless, if the device goes out of coverage of that cell, it will have to perform the authentication procedure again, which consumes energy and time. In uplink communication, Frequency Division Multiplexing (FDM) is used, while in downlink communication, Time Division Multiplexing (TDM) is used [32].

The main advantages of LTE-M are its data transmission rate and low latency. The maximum transmission rate is 384 kbps in the DL and 1 Mbps in the UL communication. Furthermore, its latency varies between 50 and 100 ms [32].

In [50], a monitoring system for a train in China was developed using LTE-M technology for data transmission. It was found that the average latency was 31 ms, well below the expected 50-100 ms. Additionally, the maximum data transmission rate was tested without any losses, reaching 17.71 Mbps for the UL and 19.3 Mbps for the DL.

2.1.5 Comparison of LPWAN technologies

Based on the overview of the LPWANs presented in this dissertation, it is clear that there is not a single technology that can satisfy all different requirements and needs of IoT applications. Therefore, given the characteristics of each LPWAN presented before, it is possible to conclude that each technology has its positive and negative points, and the choice of which one to use depends on the application, the location of the device's implementation, mobility, latency, the required data rate, among other factors. Table 2.3 summarizes the main characteristics of the four LPWAN networks discussed in this section.

Table 2.3: Main characteristics of networks: LoRaWAN, Sigfox, NB-IoT and LTE-M.

	LoRaWAN	**Sigfox**	**NB-IoT**	**LTE-M**
Standardization	LoRa Alliance	Sigfox	3GPP	3GPP
Frequency (BR)	915 MHz	915 MHz	Licensed band	Licensed band
Bandwidth	250 kHz/125 kHz	100 Hz	200 kHz	200 kHz
Data rate Maximum	50 kbps	100 bps	220 kbps	1 Mbps
Bidirectional	Yes	Yes (limited)	Yes	Yes
Max. packets/day	unlimited*	140 (UL) e 4 (DL)	unlimited	unlimited
Max. payload size (bytes)	243	12 (UL) e 8 (DL)	1600	1000
Energy Consumption	Low	Very Low	Medium-Low	Medium
Link Budget	154 db	159 db	151 dB	146 dB
Max. Range (km)	20 (Rural), 5 (Urb.)	40 (Rural), 10 (Urb.)	10 (Rural), 1 (Urb.)	5
Adaptive data rate	Yes	No	No	No
(Re-)Authentication at each Base Station	No	No	Yes	Yes
Allows private network	Yes	No	No	No

Regarding the maximum packets transmissions allowed per day, in a private LoRaWAN network, users can transmit unlimited packets daily. In contrast, public LoRaWAN networks often impose limits on packet transmissions or adopt a pricing model based on the number of packets sent.

In [51], a comparison of the LoRa, Sigfox, and NB-IoT technologies was made. The work concluded that NB-IoT offers better QoS, lower latency, larger payload size, and greater coverage, allowing for the integration of up to 100,000 devices in a cell. On the other hand, LoRa stands out for its low consumption (Class A), the possibility of creating a private network, and low cost. Additionally, by using LoRa Class C, it is also possible to achieve low latency. Finally, Sigfox is recognized for its low consumption, long range, and low cost.

In [32], a comparison of the four LPWAN technologies discussed in this section is also provided. The work concluded that LoRaWAN offers the best energy efficiency, while NB-IoT is the most suitable for high transmission rates. Sigfox is the best solution for very low transmission rates and, finally, LTE-M is recommended when high transmission rates and low latency are needed.

In recent years, various studies have investigated the capabilities and applications of Low Power Wide Area Networks (LPWANs). As summarized in Table 2.4, different methodologies reveal distinct attributes of each LPWAN technology. In general, the table provides a comprehensive overview of the contributions made by various works on LPWAN technologies in different contexts, enabling better-informed decisions based on specific application requirements.

Table 2.4: Summary of works on LPWANs and their main conclusions.

Ref.	**Methodology**	**LPWANs**	**Contribution**
[47]	Field tests	Sigfox	Location system using RSSI from Sigfox transmissions. Average location error of 340m.
[32]	Analysis	LoRaWAN, Sigfox, NB-IoT and LTE-M	LoRaWAN: Better energy efficiency; Sigfox: Recommended for very low transmission rates; NB-IoT: High transmission rate; and LTE-M: High transmission rate and low latency.
[43]	Analysis/ Simulation	LoRaWAN, Sigfox and NB-IoT	NB-IoT is more suitable for water treatment measurement systems due to its greater scalability and ability to support more devices with a lower error rate.
[49]	Field tests	NB-IoT	Smart factory application using NB-IoT. Average delay of 182 ms. Assessment of the financial cost of the solution.
[51]	Analysis	LoRaWAN, Sigfox and NB-IoT	LoRaWAN: Low consumption, possibility of creating a private network and low cost; Sigfox: Low consumption, long range and low cost; and NB-IoT: Better QoS, lower latency, higher payload and greater capillarity.
[40]	Field tests	LoRaWAN	Vital data monitoring with LoRaWAN. 96.7% delivery rate without using ACK or retransmissions.
[41]	Field tests	LoRaWAN	Location system using Time Difference of Arrival in a public LoRaWAN network. Average location error of 200m.
[48]	Analysis	NB-IoT	NB-IoT is not recommended for mobile devices.
[45]	Field tests	Sigfox	Monitoring the activity of elderly people at home using door and presence sensors with the Sigfox network.

A relevant comment regarding LoRaWAN is that the protocol itself does not impose limitations on the number of transmissions per day, as Sigfox does; however, since LoRaWAN uses a free spectrum, in Brazil it is subject to the regulations of Anatel described in Section 2.1.6, which states that a device can only transmit packets at intervals greater than 14 seconds, in addition to only being able to occupy the medium (i.e., duration of the transmission) for up to 0.4 seconds. Furthermore, it is worth mentioning that when using public LoRaWAN networks, such as those of *American Tower* in Brazil, there are also limitations regarding the daily number of *uplink* and *downlink* transmissions according to the data plan contracted, which does not apply when using private LoRaWAN networks.

2.1.6 LPWAN's - Brazilian Legislation (Anatel)

The resolution No. 14448 [52], of December 4, 2017, from Anatel describes the regulation of the use of ISM (Industrial Scientific and Medical) radio frequency bands, which include the frequencies used by LoRa and Sigfox in Brazil (915 to 928 MHz). Below are some topics from resolution No. 14448 that apply to the regulation of this band:

> *10 - EQUIPMENT USING SPREAD SPECTRUM TECHNOLOGY OR OTHER DIGITAL MODULATION TECHNOLOGIES*
>
> - *10.2.1 - Carrier frequencies of the hopping channels should be separated by at least 25 kHz or by the channel bandwidth at 20 dB, with the larger value considered;*
> - *10.2.3 - The system should jump to the selected frequencies at the hopping rate from a list of ordered pseudo-randomly selected frequencies;*
> - *10.2.4 - Each transmitter should, on average, use each of the frequencies equally when transmitting continuously;*
> - *10.2.5 - In addition to the requirements stated in the previous items, the following requirements apply to frequency-hopping systems operating in the 902-907.5 MHz and 915-928 MHz bands:*
>   - *10.2.5.1 - The peak output power of the transmitter should not exceed 0.25 W for systems using less than 35 hopping channels;*
>   - *10.2.5.2 - If the channel bandwidth at 20 dB is less than 250 kHz, the system should use at least 35 hopping frequencies and the average occupation time of any frequency should not exceed 0.4 seconds in a 14-second interval;*
> - *10.6 - The radio frequency power produced in any 100 kHz bandwidth outside of any of the bands in which the system is operating, as established in this item, should be at least 20 dB below the maximum power produced in a 100 kHz bandwidth within the operating band.*

Understanding country regulations is crucial when developing Internet of Things (IoT) solutions, as compliance with legal frameworks can significantly impact both the design and requirements of these applications. Different countries may impose specific requirements related to data privacy, security, and wireless communication standards, which can dictate how devices operate and communicate. Some important concerns, specifically for IoT applications, are the maximum power transmission and the duty cycle.

2.1.7 Application Examples: Which technology to use?

In this section, several application examples will be addressed with an indication of which technology or technologies are the best fit according to the literature.

Agriculture – Smart Farming

In agriculture, where we will have simpler sensors such as humidity and temperature sensors, the most important aspect is battery longevity. Furthermore, these sensors will likely only need to send a few data points per day. Therefore, LoRa and Sigfox are recommended [53].

Smart Grid

In a smart electrical grid, we will have stationary devices that, for example, monitor substations or the energy consumption of each customer. In both cases, a high data transmission rate and low latency are required so that the utility company can take action in case of problems. Thus, NB-IoT and LTE-M are the most recommended [54] [55].

Vending Machines

In a retailer's self-service checkout, low latency is essential for the user to have a good experience. In addition, a high transmission rate may be necessary for real-time inventory tracking and payment processing. In this case, the most suitable option is to use LTE-M due to its lower latency and higher data rate [56], although NB-IoT is also an alternative.

Monitoring of Industrial Machines

In an industry, there may be various sensors monitoring data such as motor speed, vibration patterns, or some quantity in a chemical process. Generally, low latency and high transmission rates are required. Thus, NB-IoT and LTE-M are the most recommended options [57].

Asset Tracking

Tracking cars, trucks, or even machinery is an application that demands a low data rate since most of the time it is only necessary to send latitude and longitude data, and there is not a significant requirement for latency. Furthermore, it has been observed that NB-IoT and LTE-M are not suitable for mobile devices due to the need for a lengthy authentication process every time they move out of range of a cell tower. Therefore, LoRa and Sigfox are the most recommended alternatives [58].

2.2 LoRaWAN Operation Details

LoRaWAN networks use a star-of-stars topology in which gateways relay messages between end devices and a central Network Server (NS). Then, the NS routes the packets from each device of the network to the associated Application Server allowing this information to be displayed in any application. The communication between end devices and gateways is spread out on different frequency channels and Spreading Factors (ranging from 7 to 12). The data rate (DR) is determined by the bandwidth (BW) and SF used, with the total achievable DR varying based on regional parameters. For example, in the AU915-928 band, which is used in Brazil, the DR ranges from DR0 to DR15, as shown in Table 2.5. The selection of the SF is a trade-off between communication range and message duration (the time on air, which impacts the energy consumption), as illustrated in Figure 2.6. Additionally, the bandwidth (BW) typically remains fixed, meaning the data rate (DR) is primarily influenced by the spreading factor (SF). The SF and DR are inversely related, meaning that increasing the SF decreases the DR and vice versa. This means that raising the SF lowers the data transmission rate in exchange for a higher communication range. Furthermore, the SFs are orthogonal to each other, meaning that even packets transmitted on the same channel but using different SFs do not interfere with each other. This characteristic contributes to the scalability of the network.

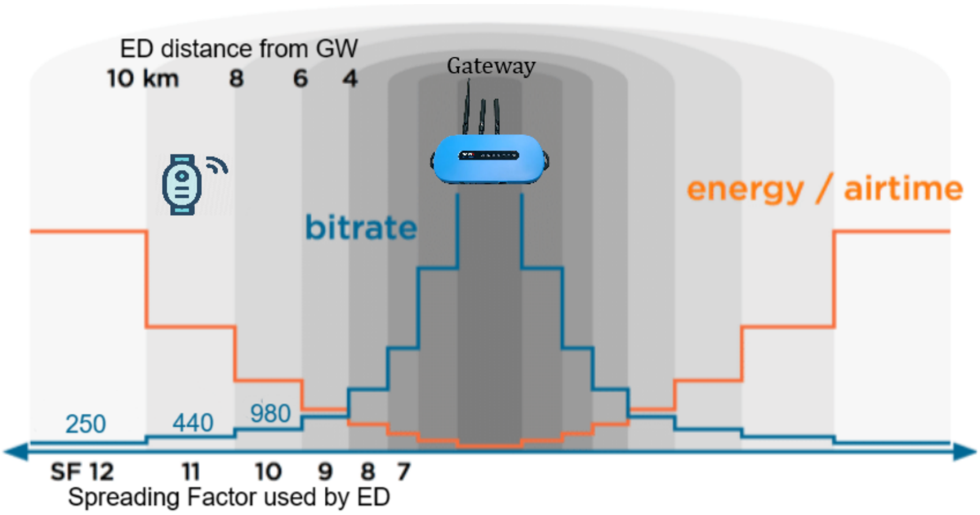


Figure 2.6: Correlation between distance, SF, bitrate, airtime and energy consumption (adapted from [4]).

In order to achieve frequency diversity to make the network more robust to interfer-

Table 2.5: AU915-928 LoRa data rate configurations [5].

Data Rate	**Configuration (SF / BW)**	**Indicative physical bit rate [bit/s]**
DR0	SF12 / 125 kHz	250
DR1	SF11 / 125 kHz	440
DR2	SF10 / 125 kHz	980
DR3	SF9 / 125 kHz	1,760
DR4	SF8 / 125 kHz	3,125
DR5	SF7 / 125 kHz	5,470
DR6	SF8 / 500 kHz	12,500
DR7	Reserved for Future Use	-
DR8	SF12 / 500 kHz	980
DR9	SF11 / 500 kHz	1,760
DR10	SF10 / 500 kHz	3,900
DR11	SF9 / 500 kHz	7,000
DR12	SF8 / 500 kHz	12,500
DR13	SF7 / 500 kHz	21,900
DR14/DR15	Reserved for Future Use	-

ences, end devices may transmit on any channel available at any time, using any available data rate, but must swap channels in a pseudo-random fashion for every transmission [59]. Each device can transmite from multiple available channels as part of its transmission process, allowing for frequency diversity and minimizing the chances of collision with other devices, helping to accommodate a larger number of devices within the network. The channel hopping is generally governed by a predefined configuration specified by the network server, which involves selecting channels at a pseudo-random sequence.

LoRaWAN employs the Adaptive Data Rate (ADR) scheme to optimize both the battery life of end devices and the overall network capacity. This feature enables the network server to dynamically adjust the SF and transmit power of end devices based on their signal strength and quality. The ADR algorithm continuously monitors the communication between the end devices and the gateway, using the received signal strength indicator (RSSI) and signal-to-noise ratio (SNR) to determine the optimal data rate and transmit power for each device. Unlike analyzing the overall distribution per SF, the algorithm focuses on individual SF allocation to minimize power consumption for each ED.

RSSI (Received Signal Strength Indicator) is a relative measurement that indicates whether the received signal is sufficiently strong to demodulate the transmitted packet. Given that LoRaWAN enables bi-directional communication, RSSI is a crucial metric for both gateways and end devices. Measured in dBm, RSSI values are typically expressed in negative numbers. The closer the RSSI value is to zero, the stronger the received signal. SNR is a measure used to quantify the level of a desired signal compared to the level of background noise. It is typically expressed in decibels (dB) and can be calculated using

Table 2.6: Minimum SNR required for demodulating each SF [6].

Spreading Factor	**Minimum SNR required**
7	-7.5 dB
8	-10 dB
9	-12.5 dB
10	-15 dB
11	-17.5 dB
12	-20 dB

the following formula:

$$SNR\,(dB) = RSSI\,(dBm) - P_{noise}\,(dBm). \tag{2.1}$$

A higher SNR indicates a clearer and more reliable signal, as it means that the signal is stronger than the noise. If the RSSI is below the noise floor, we'll have negative values of SNR. However, LoRa is capable of demodulate signals that are below the noise floor. The minimum SNR required for demodulating each spreading factor is shown in table 2.6.

2.2.1 MAC Commands

MAC (Medium Access Control) commands in LoRaWAN are used for various purposes such as configuring the end devices, choosing communication parameters, and requesting specific actions. These commands are essential for managing the communication parameters of the end devices and ensuring efficient and reliable operation within the LoRaWAN network. Typically, these commands are sent by the network server to the end devices but some of them are replies from the EDs to the NS.

For example, in the ADR scheme, the end device sends the LinkADRAns (Link Adaptative Data Rate Answer) command in response to the LinkADRReq command (Link Adaptative Data Rate Answer). The LinkADRReq command is sent by the network server to request adjustments to an end device's data rate, transmission output power, channels used for uplink access, and the number of transmissions made per uplink frame.

Another usefull MAC command, used specially by Class A devices, is the RXParamSetupReq (Receive Window Parameters Setup Request) command, that is sent by the network server, to request updates to the data rate offset between the uplink and the first receive window (RX1), as well as the frequency and data rate for the second receive window following an uplink (RX2). The RXParamSetupAns (Receive Window Parameters Setup Answer) command indicates whether the end device successfully applied the requested settings.

The PingSlotInfoReq (Ping Slot Information Request) is sent by end devices using Class B to inform the network server of its intent to change the periodicity of its ping slots. The network server responds with the PingSlotInfoAns (Ping Slot Information Answer) command to indicate the acknowledgment of the request.

Additionally, the replies of MAC commands can carry useful information such as the battery percentage of each device. This information can be obtained with the NS issuing a `DevStatusReq` command to the end device, which responds with a `DevStatusAns` command which contains the battery level [59].

2.2.2 Theoretical Calculation of Air Time

The transmission air time is critical for analyzing the energy consumption of battery-powered ED, because it represents the duration for which the radio is actively transmitting. Since transmission is one of the most power-hungry activities, accurately calculating air time allows for more efficient use of battery power by minimizing unnecessary transmission durations and idle times.

A raw LoRaWAN packet consists of a preamble containing control bits standardized by the protocol and a data information payload [5]. Thus, the total Air Time of a LoRa packet transmission (T_{packet}) is the sum of the preamble's ($T_{preamble}$) and the payload's ($T_{payload}$) transmission times:

$$T_{packet} = T_{preamble} + T_{payload}. \tag{2.2}$$

To calculate each of these parcels, we first obtain the transmission parameter ratio that is given by the symbol rate (R_{sym}):

$$R_{sym} = \frac{BW}{2^{SF}}, \tag{2.3}$$

where BW is the selected bandwidth (125, 250 or 500 kHz) and SF is the Spreading Factor (that ranges from 7 to 12).

Using R_{sym}, the transmission time per symbol T_{sym} is calculated as:

$$T_{sym} = \frac{1}{R_{sym}}. \tag{2.4}$$

Thus, the parcel corresponding to the transmission time of the preamble is given by:

$$T_{preamble} = (n_{preamble} + 4.25) \times T_{sym}, \tag{2.5}$$

where $n_{preamble}$ is the programmed length of the preamble, which is by default equal to 8.

The number of symbols in the payload parcel (n_p) is given by:

$$n_p = 8 + \max\left(\left\lceil \frac{8 \times PL - 4 \times SF + 28 + 16 \times CRC - 20 \times IH}{4 \times (SF - 2 \times DE)} \right\rceil (CR + 4), 0\right), \tag{2.6}$$

where:

- PL is the number of bytes in the payload (from 1 to 255);
- SF is the Spreading Factor (7 to 12);
- $IH = 0$ when the header is enabled (default) or $IH = 1$ when the header is disabled;
- $DE = 1$ when `LowDataRateOptimize`$= 1$ (only used for $SF \geq 11$);
- CR is the coding rate (1 corresponds to default coding rate 4/5. LoRaWAN also employs other code rates, including 4/6, 5/7, and 4/8).

Finally, the portion corresponding to the payload transmission time is given by:

$$T_{payload} = n_p \times T_{sym}. \tag{2.7}$$

In this dissertation, we present in Chapter 4 experimental power consumption measures of LoRaWAN end devices, using a state-of-art power monitoring equipment. The experimental values obtained will be compared with the theoretical Calculation of Air Time.

Chapter 3

Related Work

Over the past years, many studies have been done to evaluate the performance of LoRaWAN in different scenarios and to understand the scalability of this technology [60]. Among these works, some of them already propose new algorithms to better allocate in a suitable way the SFs to end devices in a LoRaWAN network. They generally focus on improving DER and the network throughput.

The authors in [21] propose two algorithms, EXPLoRa-SF and EXPLoRa-AT, to allocate SFs in LoRaWAN systems to improve DER and the network throughput. The main idea is to allocate EDs transmitting at different SFs in order to not overload some and thereby reduce the number of collisions. The EXPLoRa-SF algorithm, which selects Spreading Factors (SF) based on the total number of connected devices, equally distributes SFs to end nodes based on RSSI values and thresholds. Therefore, the number of EDs allocated to each SF (K) can be calculated as:

$$K = \frac{N_{EDs}}{6}, \tag{3.1}$$

where N_{EDs} is the total number of EDs and the 6 represents the 6 SFs possibles (SF7, SF8, SF9, SF10, SF11 and SF12).

The EXPLoRa-AT algorithm, which is a more advanced heuristic, aims to ensure a fair distribution of Air Time among the nodes in the network. EXPLoRa-AT employs the ordered water-filling approach to allocate SFs and equalize the Air Time of packets transmitted by end devices in each SF group. The ordered water-filling strategy seeks a balanced distribution of the channel load, that basically try to ensure that the sum of air times in each SF group are equal:

$$\sum_{SF7} AirTime = \sum_{SF8} AirTime = (...) = \sum_{SF11} AirTime = \sum_{SF12} AirTime. \tag{3.2}$$

As presented in Section 2.2, the AT is increased as we rise the SF, i.e. the AT of SF12 is higher than a SF7. Therefore, in order to equalize the sum of AT in each SF groups, the number of EDs allocated for each SF j (K_{SFj}) will be:

$$K_{SF7} > K_{SF8} > (...) > K_{SF11} > K_{SF12} \tag{3.3}$$

The simulation results show EXPLoRa-AT outperforms EXPLoRa-SF in terms of reliability. Furthermore, both strategies only considers the RSSI of each ED to perform the SF allocation and the energy eficiency or energy fairness are not considered.

The paper [23] proposes a reinforcement learning (RL) method called LR-RL. This method reduces packet collision rate (PCR) based on the principle of SF-channel traffic equilibrium, which indicates that SFs with higher data rate must undertake higher packet loads. The performance of LR-RL is compared with other SF allocation methods such as LR-opt-pro and LR-greedy, both proposed in the same paper, showing that it has lower PCR compared to these. However, the paper does not provide any analysis of LR-RL with other existing SF allocation methods in terms of network throughput, latency, or energy efficiency.

The work in [61] presents a scheme to optimize the packet error rate for users far from the base station, thereby improving fairness in these networks. This is achieved by improving the channel, SF and power transmission selection for each node. The paper validates the proposed algorithm by implementing it in NS-3 and comparing it to a scheme similar to ADR, efficiently controlling the power and spreading factor for each node, while avoiding near-far problems by allocating distant users to different channels. The near-far problem mentioned consists that nodes far from the base station are more willing to collisions then near nodes, causing an unfair packet error rate in the network. With this method, simulations show that the packet error rate can be decreased up to 50% for edge nodes. However, choosing a specific transmission channel goes against the LoRaWAN standard, which requires EDs to swap channels in a pseudo-random fashion for every transmission.

The proposal of AdapLoRa [62] addresses the issue of unfair energy consumption in LoRa networks due to static SF allocation, in which devices using a slower SF results in a faster battery depletion and reduced network lifetime. AdapLoRa proposes a dynamic network resource allocation system that periodically adapts resource allocation considering the current estimated network lifetime, link quality variations, and network interference. It also considers the energy consumed by end devices to receive the configuration commands, ensuring that adaptation overhead is taken into account.

The proposal of [22] has two innovative schemes, EXPLoRa-KM and EXPLoRa-TS, based on the ordered water-filling approach that is also used in the EXPLoRa-AT. The EXPLoRa-KM uses K-means clustering to reduce the load in critical regions with a significant number of collisions by computing suitable adjustments on the SF allocation in these areas. The EXPLoRa-TS performs an equalization of the traffic load among the SF

Table 3.1: Summary and comparison with previous work.

Ref.	Summary	Network performance	Energy efficiency	LoRaWAN compatible	Exp. Analysis
[21]	Improve DER by SF allocation	✓		✓	
[23]	Reduce packet collision rate (PCR)	✓		✓	
[61]	Optimize the packet error rate for users far from the base station	✓			
[62]	Improve energy consumption fairness by a dynamic network resource allocation		✓	✓	✓
[22]	Enhance network performance and scalability	✓		✓	
[63]	Improve energy consumption fairness		✓	✓	
BLO	Optimize the Battery Life through periodic SF reallocation	✓	✓	✓	✓

channels, taking into account that each device can transmit a variable amount of data at a different sending rate. Simulation results show that both EXPLoRa-KM and EXPLoRa-TS enhance network performance and scalability in LoRaWAN networks for heterogeneous IoT scenarios, when different traffic loads are generated around a LoRaWAN Gateway.

The paper [63] proposes a networking solution called EF-LoRa to achieve fair energy consumption among end devices in LoRa networks. It formulates the energy fairness problem as an optimization problem, that seeks to allocate different network resources, including frequency channels, spreading factors, and transmission power. The proposed EF-LoRa solution improves the energy fairness of legacy LoRa networks by 177.8% according to simulation results. However, it only considers the energy efficiency.The optimization of the LoRaWAN performance is not considered.

Table 3.1 shows the comparison of existing studies regarding some important aspects as the network performance analysis, energy efficiency, compatibility with the LoRaWAN standard and experimental contributions. Our main contribution is a periodic SF allocation scheme that considers the current battery of each device, improving the energy consumption fairness while also carrying about the network performance.

Chapter 4

Power Consumption Experimental Evaluation

This chapter describes the methodology used in this dissertation to evaluate the energy consumption on LoRaWAN devices. We present the state-of-art measurement tool used and show all the experimental results.

4.1 Experimental Setup

Several papers have developed models to evaluate the energy consumption of LoRaWAN end devices using distinct LoRaWAN simulations tools [64] [65]. However, experimental evaluations of energy consumption in the literature remain limited, primarily due to their low-power nature and the challenges associated with acquiring measurement tools that provide sufficient precision. This dissertation tries to fill this gap experimentally evaluating a LoRaWAN ED energy consumption, focusing on the energy drained regarding the radio transmissions. To measure the consumption of LoRa transmissions, a *Power Profiler Kit II* (PPK2) device from Nordic Semiconductor was used, which is a tool for measuring the average and dynamic power consumption in embedded low-power solutions, with a resolution that can reach up to 100 nA. The time resolution is also high enough to detect energy spikes, as seen in LoRa Transmissions. This is achieved by having a 100 ksps sampling rate of the current consumed. PPK2 is compatible with Nordic's nRF Connect for Desktop software, enabling users to view both average acquisition times and high-resolution events in the same window.

The PPK2 is driven by the nRF52840 SoC, which uses an analog-to-digital converter (ADC) to measure a voltage drop over a series of measurement resistors. It has five different measurement ranges, which are managed by an automatic switch circuitry, and supports both ampere meter and source modes, which means that it can measure and optionally supply currents ranging from sub-μA to 1 A. In the source meter mode, the PPK2 acts as both a power supply and a measurement device for the device under test, being useful when we want to control the supply voltage to the device while measuring its current consumption. While in the ampere meter mode, the PPK2 acts solely as a current measurement device, with the device under test powered by an external source. In this dissertation, the PPK2 was used only in the source meter mode, providing 3.3 V for the development board used while making the current measures, as shown in Figure 4.1.

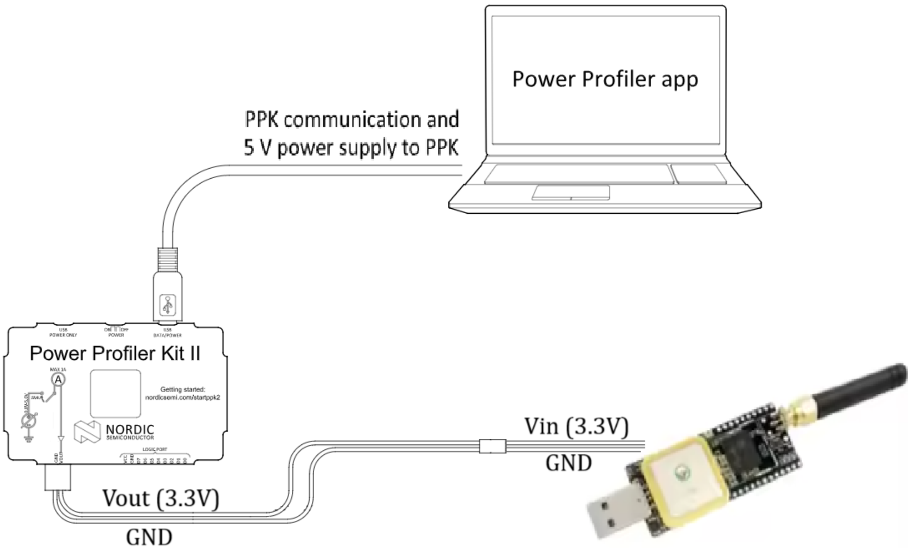


Figure 4.1: Electrical diagram of the experimental setup.

In addition, to perform the LoRa transmissions, a LilyGO T-Motion development board was used, which contains a S76G System in Package (SiP) from AcSiP. The S76G integrates an STM32L073Z microcontroller, a Semtech's SX1276 equipped with the LoRa proprietary transceiver modem, and a Sony CXD5603GF GNSS with ultra-low power consumption. The SX1276 can deliver up to +20 dBm RF output, consuming from 22 mA to 125 mA during the transmission, and a high sensitivity down to -137 dBm. This SiP is ideal for tracking applications, but as we just want to evaluate the LoRaWAN transmissions consumption, the GNSS block was turned off during the experiments. Figure 4.2 shows the experimental setup used to perform the power consumption evaluation.

4.2 Power Consumption Results

For the consumption analysis of LoRa transmissions, we use the maximum payload length for each spreading factor, as shown in Table 4.1. We also did measurements with the 51-byte payload (the maximum for SFs 10 to 12) for all SFs, to have a comparison with the same packet size. For each configuration, we perform 10 packet transmissions and measure the instantaneous current (in mA), and the time that the transceiver stays on during each transmission (in ms). This is the time during which the LoRa transceiver is in

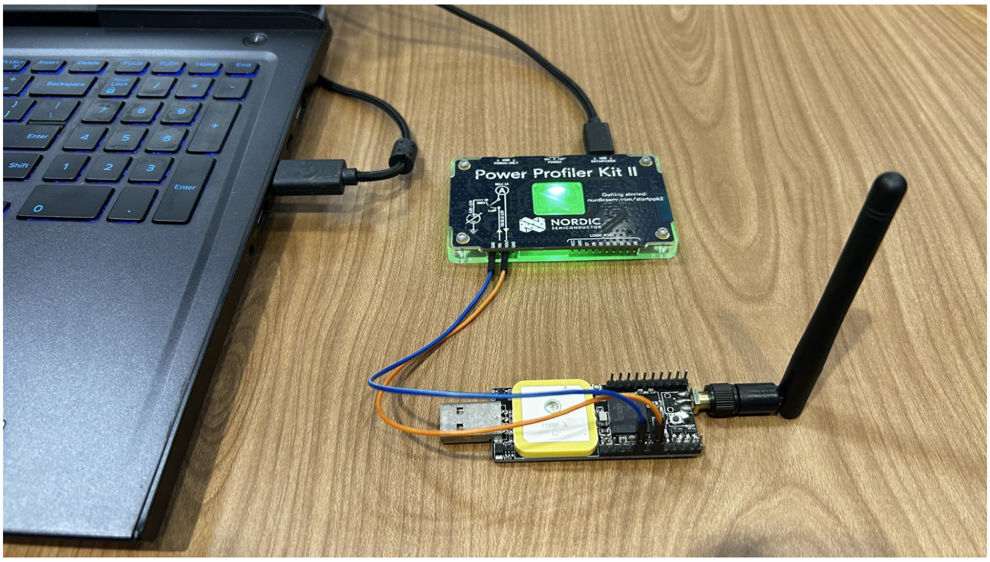


Figure 4.2: Experimental setup.

Table 4.1: Bit rate and maximum payload considering the AU915-928 and BW of 125 kHz.

DR	SF	Bit rate	Maximum Payload
0	12	250 bit/s	51 bytes
1	11	440 bit/s	51 bytes
2	10	980 bit/s	51 bytes
3	9	1760 bit/s	115 bytes
4	8	3125 bit/s	242 bytes
5	7	5470 bit/s	242 bytes

the transmission mode. After these measurements, we can compare this experimental data with theoretical air time values detailed in Section 2.2.2, and the theoretical consumption in the transmission mode using the 20 dBm RF output.

Figure 4.3 shows a screenshot of the nRF Connect software, the graphical tool of *Power Profiler Kit II*, showing the consumption profile of a LoRaWAN 51-byte packet transmission using SF10. The x-axis represents time, while the y-axis shows the current consumption in milliamps (mA). The selected area of the plot shows the peak corresponding to the transmission current consumption, where the current reaches a maximum of 138.69 ms,to send a 51-byte payload in SF10, when the radio stays on for 698.4 ms indicating the time taken for the transmission. Also, the figure presents a Class A LoRaWAN ED power consumption. This class is characterized by a transmission period, which is characterized by a longer peak of current consumption, followed by two reception windows (RX1 and RX2), characterized by two smaller and shorter peaks. We use the LilyGO T-Motion development board to perform the experiment. We setup the device to send 10 51-byte messages with 10 seconds between each other, and repeat the procedure for each SF. As this is a commercial board, it is not possible to measure the radio transmission consumption directly, but we can infer this consumption by analyzing the operation consumption

Table 4.2: Air time and power consumption for different SFs and 51-byte payload.

	Air time			Power consumption	
	Theoretical	Experimental	Error	(µAh/packet)	(µAh/byte)
SF7	102.65 ms	118.00 ms	14.95 %	3.28	0.0643
SF8	184.83 ms	215.56 ms	16.62 %	5.99	0.1174
SF9	328.70 ms	390.17 ms	18.70 %	10.84	0.2125
SF10	616.45 ms	698.42 ms	13.30 %	19.40	0.3804
SF11	1314.82 ms	1560.72 ms	18.70 %	43.35	0.8501
SF12	2465.79 ms	2793.75 ms	13.30 %	77.60	1.5216

cycle. In idle mode, the device drains 30 mA on average, and when the radio is actively transmitting it reaches 130 mA on average, it means that the amount spent on transmission mode is around 100 mA.

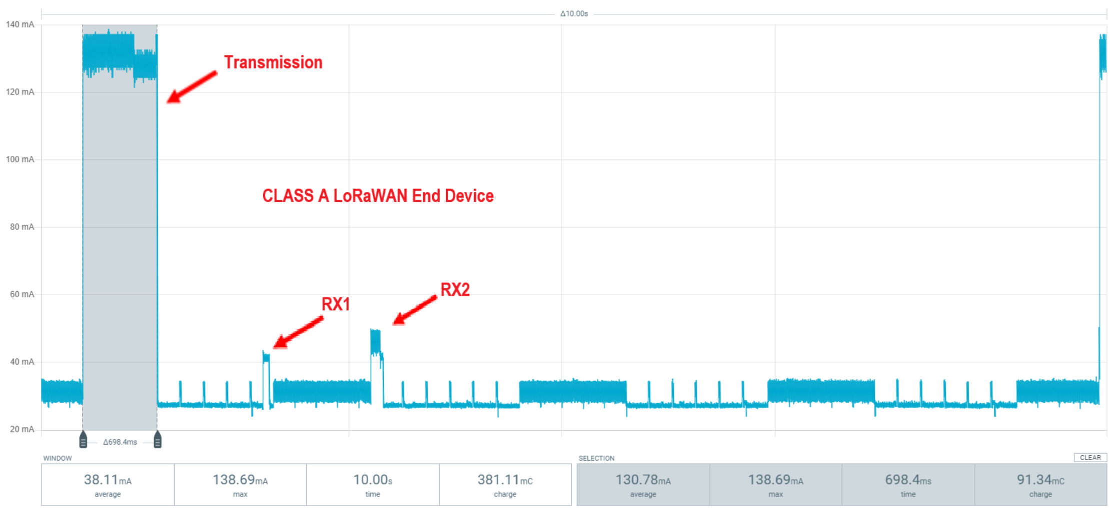


Figure 4.3: Consumption profile of a 51-byte packet transmission using SF10 (figure produced by nRF Connect Power Profiler software.).

Table 4.2 shows the experimental results using a 51-byte payload and all possible SFs. The time that the device stays in transmission mode is labeled as Air Time (AT) - Experimental. Comparing these values with the Theoretical AT formula presented in Section 2.2.2, we obtain an error rate varying from 13.3% to 18.7%, which is considered reasonable, given an experimental setting. Yet, this difference is important once the energy spent on packet transmissions is responsible for the higher part of the operation consumption cycle. Additionally, it shows the power consumption per packet transmission and per byte for this setup. For example, one transmission using SF12 costs 77.60 µAh, almost 24 times higher than with SF7 (3.28 µAh), confirming that the SF selection is extremely important for the battery life. Figure 4.4 illustrates the energy cost per byte, graphically demonstrating the difference in power consumption across various spreading SFs.

Table 4.3 shows the experimental results using the maximum payloads for each SF, as

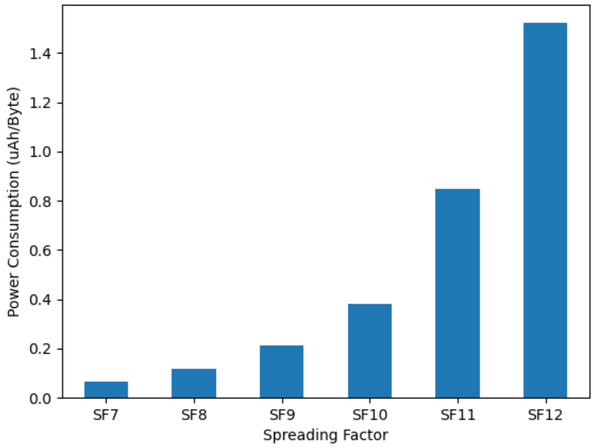


Figure 4.4: Power consumption as a function of the SF for 51-byte payload.

presented in Table 4.1. The transmissions using higher payloads show lower error between the theoretical and experimental AT. Also, comparing Tables 4.2 and 4.3, the 51-byte transmissions consume 0.0643 µAh/byte while the 242-byte ones consume 0.0459 µAh/byte. This cost per byte reduction is due to the preamble overhead, that has more impact as less payload (useful information) is transmitted, as shown in Section 2.2.2.

As mentioned before, Class A LoRaWAN devices receive messages from the network (downlink) in two distinct receive windows after transmitting an uplink message. These receive windows are referred to as RX1 and RX2. If the device does not receive any downlink data or an acknowledgment in RX1, it will subsequently open the second receive window (RX2). The duration of these windows is long enough to detect a downlink preamble. Table 4.4 shows the experimental measures of the RX1 and RX2 windows after transmitting a 51-byte payload with all possible SFs. The RX1 window duration increases as a higher the Spreading Factor is used for the uplink transmission, starting from 42.61 ms at SF7 and reaching to 114.80 ms at SF 12. This occurs because the SF used for RX1 is the same as the SF used for the uplink transmission. Nonetheless, RX2 window duration remains constant around 114.80 for all SF values. This occurs because the RX2 utilize a different SF, which can be adjusted based on network settings. In our case, the RX2 window is configured to utilize SF12, as can be observed when the RX1 for SF12 also lasts around 114.80 ms. Finally, the energy consumption related to the transmission time of a packet and the openings of the RX1 and RX2 reception windows can be compared. The energy used to transmit a 51-byte packet using SF12 is 77.60 µAh, while the energy consumption considering the two reception windows in this same configuration is 0.715 µAh, that is, the energy spent on the transmission stage is 108.53 times higher.

Table 4.3: Air time and power consumption considering the maximum payload of each SF.

		Air time			Power consumption	
	Payload	Theoretical	Experimental	Error	(µAh/packet)	(µAh/byte)
SF7	242 B	379.13 ms	399.64 ms	5.41 %	11.10	0.0459
SF8	242 B	666.11 ms	707.13 ms	6.16 %	19.64	0.0812
SF9	115 B	615.42 ms	676.91 ms	9.99 %	18.80	0.1635
SF10	51 B	616.45 ms	698.42 ms	13.30 %	19.40	0.3804
SF11	51 B	1314.82 ms	1560.72 ms	18.70 %	43.45	0.8501
SF12	51 B	2465.79 ms	2793.75 ms	13.30 %	77.60	1.5216

Table 4.4: Air Time and Power Consumption considering the maximum payload (in bytes) for each SF.

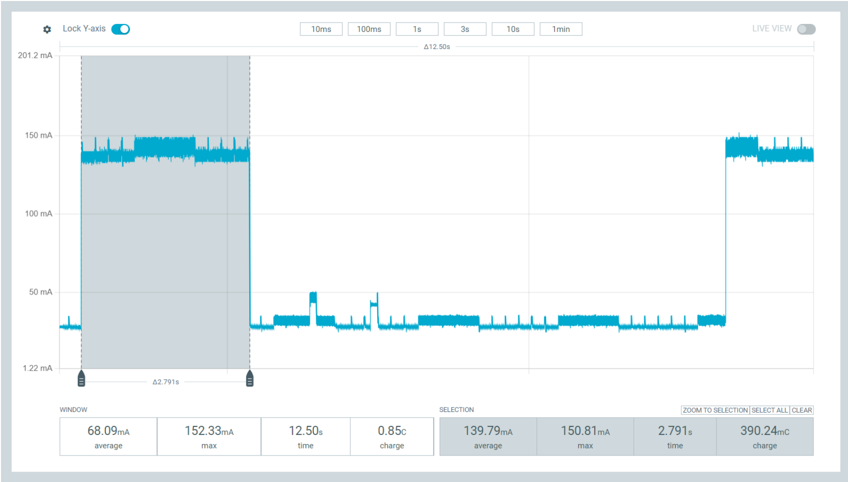
	Window Duration		Power Consumption	
	Experimental RX1	**Experimental RX2**	**(µAh/RX1 window)**	**(µAh/RX2 window)**
SF7	42.61 ms	114.79 ms	0.1327	0.3574
SF8	45.15 ms	114.74 ms	0.1406	0.3573
SF9	49.16 ms	114.81 ms	0.1531	0.3575
SF10	57.46 ms	114.80 ms	0.1789	0.3575
SF11	73.85 ms	114.76 ms	0.2300	0.3573
SF12	114.80 ms	114.80 ms	0.3575	0.3575

4.2.1 LoRaWAN Devices consumption pattern

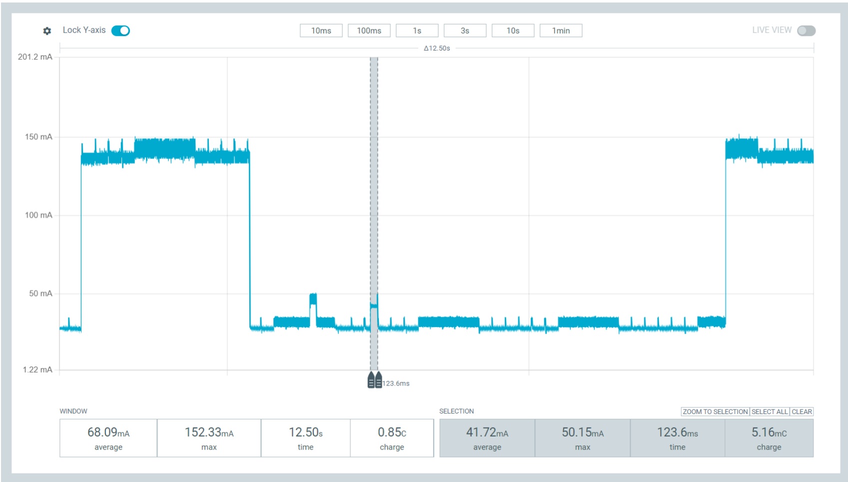
The energy consumption stages of an IoT end device can be summarized in four key phases [66] [67]: the sleep stage, where the device saves energy by entering low-power mode when the device is inactive for a long time; the idle stage, during which it processes data and performs tasks, where the power consumption is basically drained by the Microcontroller Unit (MCU); the transmission stage, which demands the highest energy as the device sends data over the network; the reception stage, where it listens for incoming information. These stages have to be considered in order to optimize power management, enhance battery life, and improve overall device performance.

Among the energy consumption stages of an IoT end device, the ones that have the most impact are the idle, transmission and reception stages. Therefore, we carried out an experimental survey to measure the energy consumption of a commercial device during these stages. Using the Power Profile Kit, we can select a time window to obtain the power consumption during each stage. Figure 4.5 shows the graph of the variation in current demanded by a class A LoRaWAN device transmitting 51-byte packets using SF12 every 10 s. The normal operating period of this class of device consists of a transmission period, which is characterized by a longer peak of current consumption (Figure 4.5(a)), followed by two reception windows (RX1 and RX2), characterized by two smaller and shorter peaks (Figure 4.5(b)), and then consumption in the idle stage, characterized only by consumption of the MCU (Figure 4.5(c)). It is important to note that during the transmission and reception phases there is also the contribution of power consumption from the

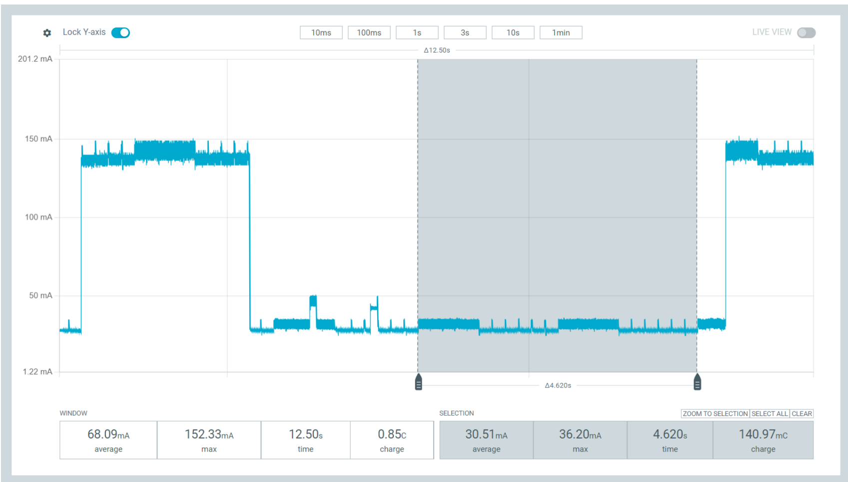
MCU. Therefore, during the transmission and reception stages it is necessary to subtract the power consumption corresponding to the MCU to infer the energy spent with communication. Table 4.5 summarizes the current and power consumed during each stage. This experimental values will be used to estimate the power consumption for each LoRaWAN transmission according to the payload size, SF and duty cycle used by the device.



(a) Average consumption during transmission.



(b) Average consumption during RX windows.



(c) Average consumption of Microcontroller.

Figure 4.5: LoRaWAN Devices consumption pattern (produced with the nRF Connect Power Profiler software.).

Table 4.6 illustrates the significant variation in the lifetime of a LoRaWAN end de-

Table 4.5: Experimental current consumption in each stage.

Stage	Current (mA)	Volt (V)	Power (mW)
Transmission (with MCU)	139.79	3.3	461.31
Reception (with MCU)	41.72	3.3	137.67
Idle (only MCU)	30.51	3.3	100.68
Transmission (only Radio)	109.28	3.3	360.62
Reception (only Radio)	11.21	3.3	36.99

Table 4.6: End Device Lifetime (in days) vs Transmissions Interval with a 2000 mAh battery.

	End Device Lifetime (in days)					
Transmission Interval	**SF7**	**SF8**	**SF9**	**SF10**	**SF11**	**SF12**
1 min	48.56	43.19	36.09	28.02	17.35	11.37
15 min	668.83	596.59	499.98	388.86	239.91	155.13
1 hour	2,382.54	2,149.94	1,830.19	1,449.63	916.62	600.88
12 hours	11,111.05	10,662.31	9,943.56	8,886.09	6,848.70	5,157.78
24 hours	13,333.19	13,004.78	12,455.69	11,591.67	9,707.90	7,877.40

vice (in days), against different transmission intervals and SF combinations, assuming a 2000 mAh battery. The presented values consider that the operation cycle of the device has 1 second in Idle mode, to wake-up and prepare the information for the transmission, then the device transmits the data with the configured SF, after which it opens the RX1 and RX2 windows and finally goes into deep sleep until the next transmission. For the Transmission, Reception and Idle stages, we considered the current consumption shown in Table 4.5. For the deep sleep current consumption, we used the values presented in the S76G SiP and STM32L073Z (the MCU inside the S76G) datasheets [68] [69], which corresponds to 5 nA. As the transmission interval increases from 1 minute to 24 hours, the device lifetime increases considerably across all SFs. For example, at a 1-minute interval, the ED lifetime is relatively short, ranging from 48.56 days for SF7 to just 11.37 days for SF12. However, as the transmission interval increases to 24 hours, the lifetime soars to nearly 13,333 days for SF7 and around 7,877 days for SF12, indicating an growth in battery life with extended transmission intervals. Overall, the data highlights not only the importance of transmission intervals in increasing the ED longevity but also the inherent trade-offs associated with varying spreading factors in LoRaWAN applications.

Chapter 5

Battery Life Optimization

The basic idea of the Battery Life Optimization (BLO) algorithm is to periodically allocate SFs to end devices to improve the fairness in battery consumption while achieving a higher DER. Fairness is reached as we use the current battery percentage under consideration to perform the SF allocation, so that devices with less remaining energy use the lowest possible SF, which minimizes energy consumption. We assume that all LoRa end devices are battery-powered and have the same battery capacity. End devices may be mobile or mounted at a fixed location. The battery level of each device can be obtained with the `DevStatusReq` command presented in Section 2.2.1.

The selection of a specific SF value depends on the value of the current battery percentage and the Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR) with which the messages of each device arrive at the gateway. These metrics restrict the choice of SFs the device may use.

The RSSI value is affected by several factors, including the device's power transmission, the distance between the device and the gateway, obstacles and environmental characteristics. An end device, according to its RSSI, has a minimum Spreading Factor that it can use to maximize the probability that the transmitted packet will be correctly demodulated at the gateway. This minimum possible SF is used as an input to our optimization problem to guarantee that the ED uses this SF or a higher one.

The main objective of BLO is to minimize the overall network energy consumption, in a fair way, considering the current battery of each device. The problem can be formulated as a Mixed Integer Linear Problem (MILP). The notations used in the formulation are shown in Table 5.1.

The first step is to verify what is the minimum SF that each device can use in order to reach the gateway, given its current RSSI. With this information, we calculate the energy cost of each node i to transmit using each viable SF as:

$$C_{ij} = M_i \times E_j, \tag{5.1}$$

Table 5.1: Notations used in the MILP formulation of BLO.

Variable	**Meaning**
$\mathcal{N}$	Set of nodes
$\mathcal{S}$	Set of SFs
M_i	Total packets sent in each interaction
E_j	Energy cost per packet, for each SFj
P_i	Remaining Battery of node i (mAh)
β_j	Number of nodes in each SFj
w_j	Air Time weight for SFj
AT_j	Air Time for SFj (ms)
C_{ij}	Cost of node i using SFj
x_{ij}	Entry of output vector containing SFj chosen for node i

where M_i is the number of packets that node i will transmit before another execution round of the algorithm and E_j is the cost per packet sent using SFj, which was obtained experimentally (Section 4.2). We define the execution round as the period during which the ED sends all the M_i packets before the gateway runs the BLO algorithm again. If the node is so far from the gateway that it is out of range of the gateway regardless the SF used, the cost is defined as infinity in the formulation: $C_{ij} = \infty$.

Therefore, the MILP problem is formulated as follows:

$$minimize \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{S}} \frac{C_{ij} x_{ij}}{\mathcal{P}_i} \tag{5.2}$$

$$\sum_{j \in \mathcal{S}} x_{ij} = 1, \forall i \in \mathcal{N} \tag{5.3}$$

$$\sum_{i \in \mathcal{N}} x_{ij} \leq \beta_j, \forall j \in \mathcal{S} \tag{5.4}$$

$$C_{ij} x_{ij} \leq P_i, \forall i \in \mathcal{N}, \forall j \in \mathcal{S} \tag{5.5}$$

$$x_{ij} \in \{0, 1\}, \forall i \in \mathcal{N}, \forall j \in \mathcal{S} \tag{5.6}$$

The objective function is defined in Equation 5.2. We define $\mathcal{P}_i$ as the amount of energy still available at node i, in mAh. The idea is to weight the cost $\mathcal{C}_{ij}$ by the amount of energy available so that nodes with more energy have lower cost. Therefore, the algorithm prioritizes smaller SFs, with lower energy cost for devices with less battery. Equation 5.3 forces that only one SF is allocated for each device. Equation 5.4 guarantees that the number of devices in each SF do not exceed the optimal distribution calculated (represented by β_j), as will be discussed next. Equation 5.5 ensures that the allocation does not exhaust the battery of the device until the end of the $\mathcal{M}_i$ transmissions. Finally, Equation 5.6 specifies the output variable x_{ij} which indicates whether node i is configured with SFj.

To define the overall allocation (β_j), i.e. the proportion of devices in each SF group, BLO uses the strategy to equalize the total Air Time (AT) of packets transmitted by EDs in each SF group, in order to reduce the collisions in larger groups using the same SF, especially the lower data-rate ones which have higher AT. First, we calculate the air time weight for each SF based on the relative proportion to the shortest SF (i.e., 7):

$$w_j = \frac{AT(SFj)}{AT(SF7)}, \qquad j = \{7, 8, 9, 10, 11, 12\}. \tag{5.7}$$

In order to exemplify the logic, consider a 51-byte payload. According to Table 4.2, $AT(SF7) = 118\,\text{ms}$ and $AT(SF8) = 215.56\,\text{ms}$. Then, we have:

$$w_8 = \frac{AT(SF8)}{AT(SF7)} = \frac{215.56}{118} \approx 1.83. \tag{5.8}$$

Then, we can calculate the congestion channel index vector (V_j), as proposed in [21]. The main idea is to fill each V_j with EDs using the weight vector calculated w_j , using a water filling strategy, so that all EDs are allocated to one SF and all have approximate values in the congestion channel index vector, considering the 51-byte payload, as shown in Figure 5.1. To guarantee that $V_7 \approx V_8$, as $w_7 = 1$ and $w_8 = 1.83$, as shown in Equation 5.8, we allocate approximately 1.83 times more devices in SF7 as compared to SF8.

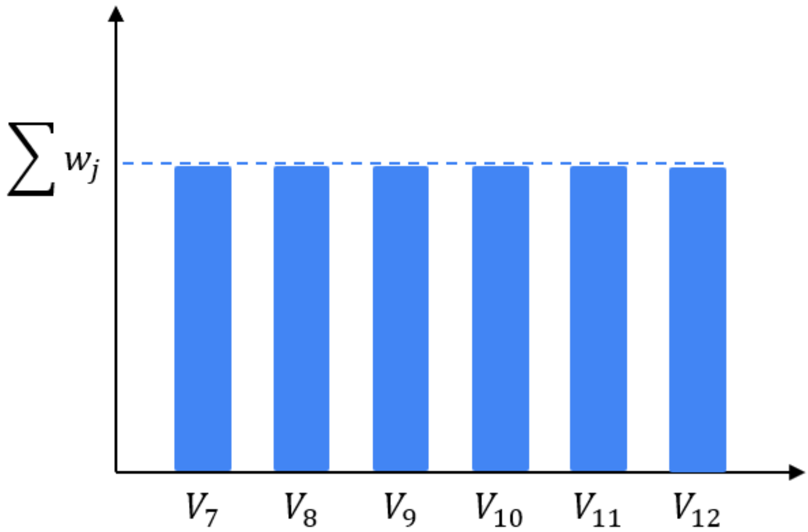


Figure 5.1: Water filling strategy to equalize the AT in each SF.

After this procedure, we can compute the overall allocation for each SF (β_j):

$$V_j = \beta_j \times w_j \rightarrow \beta_j = \frac{V_j}{w_j}, \quad \forall j \in \{7, 8, 9, 10, 11, 12\}. \tag{5.9}$$

5.0.1 Integrating BLO in LoRaWAN

The integration of the proposed BLO scheme (presented in Chapter 5) in a LoRaWAN network is simple and does not require modifications to the protocol or any information which is not already available at the NS (Network Server). The suggested integration considers the BLO Application running on the LoRaWAN NS, as shown in Figure 5.2. BLO uses the Signal-to-Noise Ratio and RSSI information, both measured by the LoRaWAN GW, the packet loss ratio computed by the NS, and the battery information that, as presented before, is obtained from the `DevStatusAns` reply message which is periodically sent by the device to the NS (after receiving the `DevStatusReq` message).

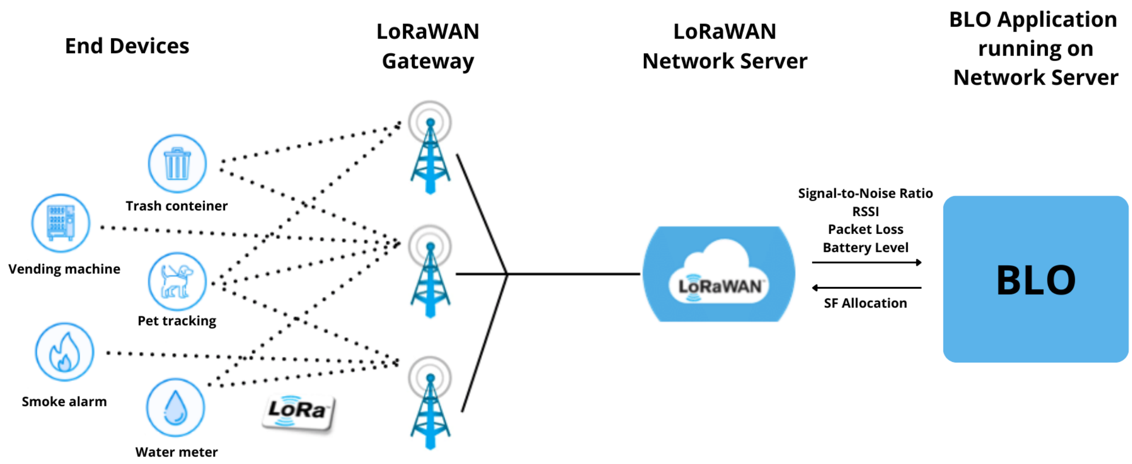


Figure 5.2: BLO integration with LoRaWAN, running on the Network Server.

To enhance the reliability of uplink communication, we first collect the maximum Signal-to-Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) from recent transmissions, which provides a benchmark for optimal performance. Next, we establish the minimum required SNR and RSSI necessary for demodulating uplink signals based on the current communication parameters, also considering the historical packet loss information. In cases when there are fewer available uplink measurements than needed, it is crucial to incorporate a safety margin to select the lowest acceptable spreading factor (SF), ensuring that sufficient margin remains for robust transmission. Once the lowest spreading factor is determined, alongside considering the battery status of each connected device, we execute the BLO (Battery Life Optimization) algorithm to carry out a new SF allocation, thereby enhancing overall system efficiency and device longevity.

In terms of computational resources, the proposed BLO algorithm is computationally lightweight, as the optimization process for allocating SFs only occurs periodically, specifically after each round. A round can be defined by a total number of transmissions or a configurable amount of time, e.g. one hour, allowing for efficient processing without placing excessive demands on the NW's computing power. Once the optimized allocation is computed, after each round, the `LinkADR` message is sent to each node to setup the optimized SF value, so the node can change to the one defined by the BLO.

Chapter 6

Performance Evaluation

This chapter discusses the results obtained from the simulations to evaluate the performance of the proposed Battery Life Optimization (BLO) scheme. We first present an overview of several updated network simulation tools, focusing on NS-3, the one used in this dissertation. We also present the simulation parameters and the python script that was developed to facilitate the performance evaluation. We then evaluate the results of LoRaWAN networks using fixed SFs, in order to understand the impact of SF selection, specially in heavy-traffic scenarios. Later, we compare BLO with ADR and two other state-of-the-art SF allocation schemes, focusing on the Data Extraction Rate and Battery consumption analysis.

6.1 NS-3 Simulation

LPWAN simulation tools are indispensable for the development of IoT, offering a controlled environment to evaluate performance, manage scalability, test security and compare technologies. They enable developers and researchers to optimize network configurations and ensure efficient, secure, and reliable IoT applications. Regarding LoRaWAN systems [70], these tools, such as NS-3 [71], Flora [72] and LoRaSim [73], offer developers and researchers the ability to model network behavior under various conditions, such as different node densities, mobility patterns, and environmental influences [74]. They allow users to simulate the performance of gateways and end devices, evaluate the impact of parameters such as transmission power, data rates, and interference, and assess the overall network capacity and coverage.

In this dissertation, NS-3 was used. Among the characteristics of this simulation tool, we can highlight that it is a discrete-event simulator that supports a wide range of network protocols, architectures, and technologies. It has several open modules for LoRaWAN and also allows the user to adapt the simulator for his own purpose. The work in [71] has presented a comprehensive survey of the available tools for simulating LoRa networks in the NS-3 network simulator. The study has highlighted the implementation, features, and limitations of each tool, providing valuable insights into the world of LoRaWAN system simulations. In our case, we develop a Python script to input the simulation parameters in an open-source LoRaWAN module, such as the number of EDs, the maximum distance of the ED around the GW, the SF used and payload size. NS-3 is capable of evaluating key performance metrics, such as the total number of successful packet transmissions and energy consumption, which were previously established using experimental data collected during our research.

The NS-3 LoRaWAN module used in this dissertation was developed as part of a master's thesis at the University of Padova and can be downloaded from [75]. The version used was the 3.0.1. The main advantage of this module is that it contains a series of classes and examples aimed at modeling the modulation and medium access technology of a LoRaWAN network, facilitating new implementations. This module includes two main models: one for the LoRa PHY layer that needs to represent LoRa chips and the behavior of LoRa transmissions, and one for the LoRaWAN MAC layer, that needs to behave according to the official specifications. Currently, only Class A end Devices are supported. To perform the evaluation with the benchmark proposals, we use EXPLoRa [21] and ADR example codes which are also provided by the module. We choose EXPLoRa to compare because it has a similar heuristic of BLO proposal that is equalize the time-on air of the EDs transmitting at the different SFs, but the major difference is that EXPLoRa is not a dynamic algorithm and do not consider the remaining battery information.

6.2 Simulation Scenario

We use the NS-3 simulator [76] to evaluate the performance of BLO. The baseline benchmark is ADR, the allocation scheme included in LoRaWAN [59]. We also simulate other two solutions of the state-of-the-art, EXPLoRa-SF and EXPLoRa-AT, described in [21]. We evaluate different scenarios where N end devices are randomly distributed in a bi-dimensional space around a single gateway (GW). The default payload size is 51 bytes, the highest possible value for SFs 10, 11 and 12, as shown in Table 4.1. The idea is to simulate the heaviest load in the network. In most cases, unless otherwise specified, the packet transmission interval is 60 s, with the aim of simulating specific applications that demand high data traffic. Simulation results are presented with 99% confidence intervals. End devices use the communication transmission parameters listed in Table 6.1.

A Python script was developed to conduct the performance evaluation. This simulation flow of the performance evaluation is represented in Figure 6.1. The script allows the user to insert the simulation parameters as the number of EDs, radius of geographical distribution, number of rounds of simulation, payload size, transmission interval and total number of transmissions. Then it inputs these parameters into NS-3 to perform the simu-

Table 6.1: Configuration parameters used in the simulations.

Parameter	Value
Carrier Frequency	915 MHz
Bandwidth	125 kHz
Code Rate (CR)	4/5
Duty cycle	[0.027 – 10] %
Message size	51 bytes
Message period	[10 – 3600] seconds
Number of gateways	1
Number of nodes (N)	10 – 1000 (typ. 500)
Path loss parameters	$d_0 = 40\,\mathrm{m}$, $\gamma = 2.08$, $\sigma^2 = 0$, $L_{pl}(d_0) = 127.41$ dB

lation of the ADR of LoRaWAN. This first results provide the minimum SF possible for each device, information that will be used as input for the BLO and EXPLoRa algorithms. For BLO, the battery level information is also registered and used as input.

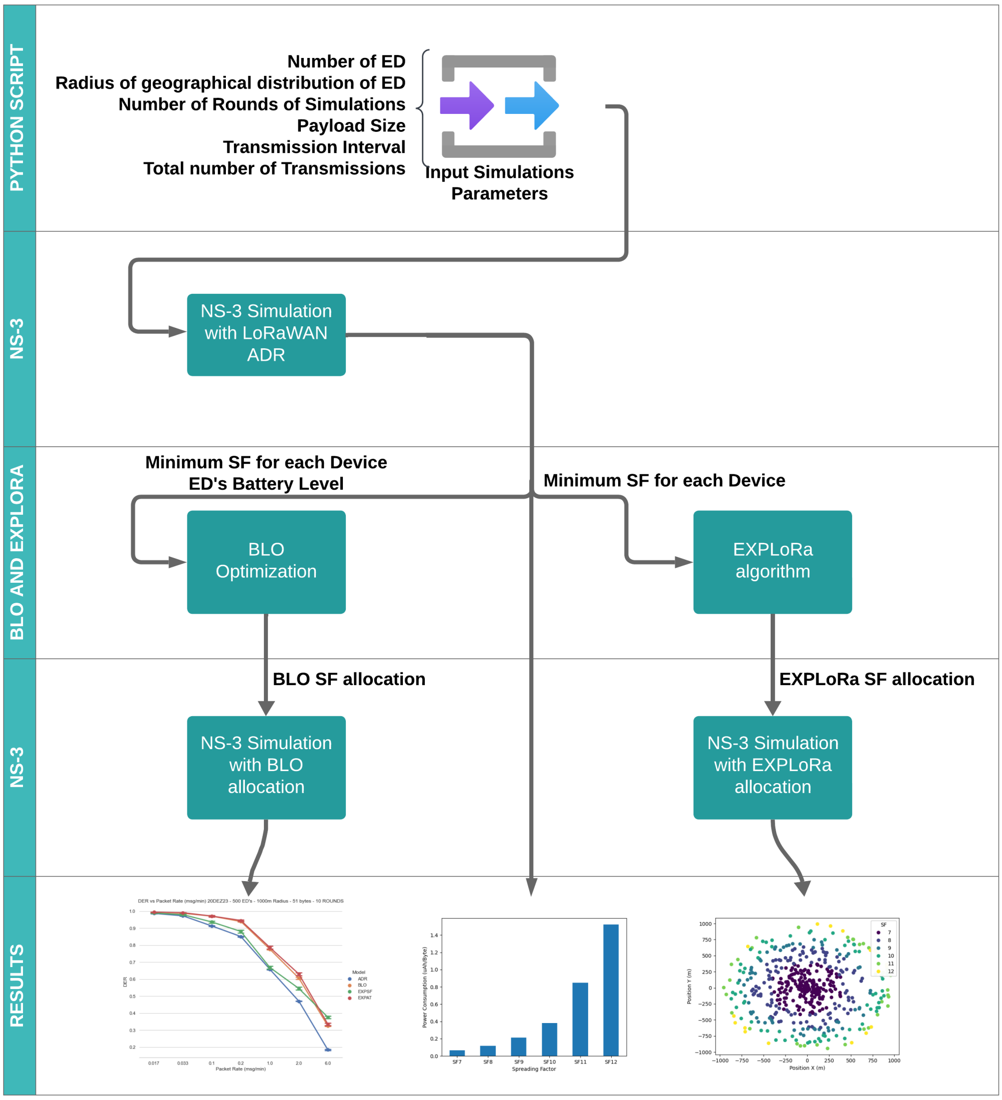


Figure 6.1: Simulation flow used for the performance evaluation.

To compare BLO with other approaches, we use the DER metric as defined in [21], i.e., the ratio of messages that are correctly received by the GW to the total number of messages transmitted by all network EDs, within a time frame. The DER assesses the overall behavior and scalability of the network, instead of the individual node performance.

6.3 Impact of Spreading Factor allocation

We begin by simulating a LoRaWAN network considering that all devices used the same spreading factor. Figure 6.2 shows the variation of the DER as the number of devices increases in a LoRaWAN network, using only fixed SFs and considering a scenario using 51 bytes transmissions with 60 s of interval. All EDs are in a maximum distance from the GW that allows them to use any SF. DER, shown on the vertical axis, represents the efficiency of data transmission, with a value of 1.0 indicating perfect data extraction (no packet collisions). Each curve corresponds to a specific spreading factor (SF7 to SF12), representing the case that all EDs in the network uses the same SF. As expected, SF7 keep the highest DER as the network size increases ,while SF12 achieves the worst DER for all number of devices. This occurs because as higher the SF we have a higher air time causing more packet collisions on the network. For the same reason, as we rise the number of EDs in the network more collisions will happen, representing a drop in the value of DER. This result shows that choosing the same SF for all devices, which is the easiest mode of SF allocation, will lower the performance of the network, especially in heavy-traffic situations with hundreds of EDs.

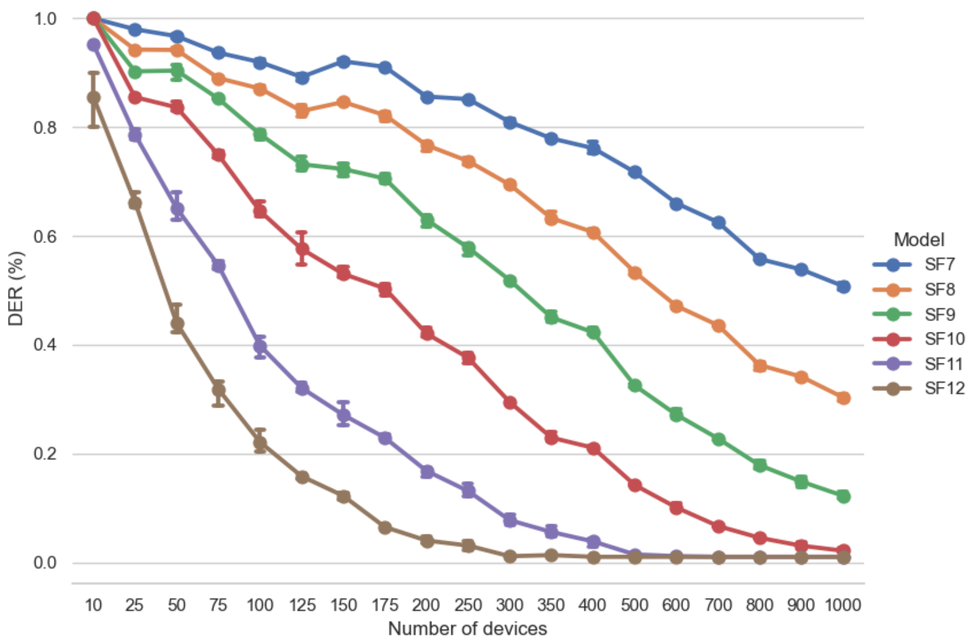


Figure 6.2: DER as a function of the number of EDs, using fixed SFs.

Figure 6.3 shows the variation of the DER as a function of the maximum distance (in meters) where end devices are located in a LoRaWAN network using only fixed SFs, considering a scenario of 1000 EDs using 51 bytes transmissions with 60 s of interval. The maximum distance parameter indicates that the devices are randomly distributed within a range from 0 up to the maximum distance from the gateway. The DER, shown on the vertical axis, measures the efficiency of data transmission, while the radius on the horizontal axis represents the maximum distance between devices and the gateway. SF7 achieves the highest DER at smaller distances, with values exceeding 0.6, but its performance declines sharply as the radius increases beyond 5,000 meters, probably indicating its limited range. In contrast, higher SFs like SF11 and SF12 maintain more consistent DERs at larger distances but exhibit significantly lower DER. Mid-range spreading factors, such as SF8 and SF9, provide a balance, with SF8 maintaining relatively stable performance until about 7500 meters. This result highlight the trade-offs between range and data extraction efficiency for each spreading factor. It is also important to highlight the importance of selecting the appropriate spreading factor based on the network's spatial requirements.

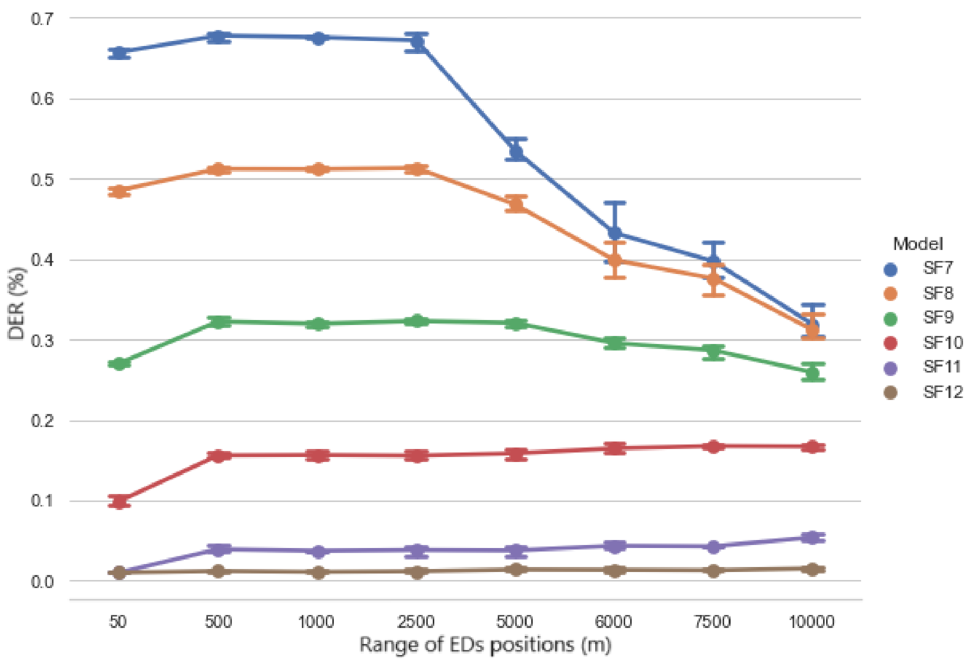
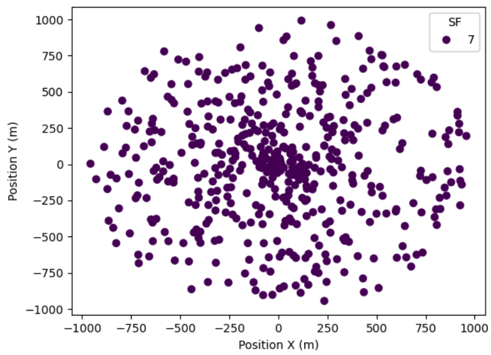


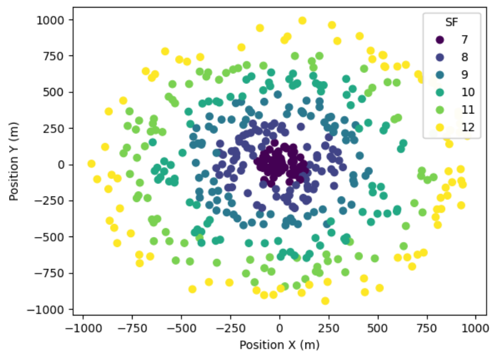
Figure 6.3: DER as a function of the maximum range where EDs are located, using fixed SFs.

6.4 Spatial Distribution of all algorithms

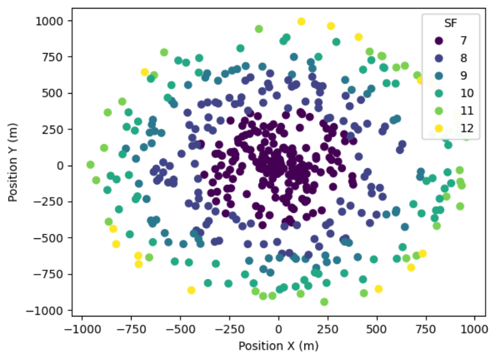
An example of the spatial distribution of SFs allocated by the different algorithms is shown in Figure 6.4. In this scenario 500 devices are distributed over a circle of 1000 m around the LoRa GW. All devices are within range of the GW independently of the SF chosen. ADR chooses the same SF for all devices, therefore producing the highest collision probability. EXPLoRa-SF distributes the devices into 6 equal groups and allocates the SF according to the RSSI of each device, meaning that the devices close to the GW use SF7, whereas farther devices are allocated higher SFs. EXPLoRa-AT allocates the maximum number of devices per SF using the channel congestion strategy, also considering the RSSI of each device. Therefore, the geographical distribution is similar to the EXPLoRa-SF pattern, which means devices close to the GW will be assigned lower SFs. Finally, BLO uses the overall distribution (number of devices allocated in each SF), similar to EXPLoRa-SF, but considering the current battery level in addition to the RSSI of each device. The BLO strategy produces an SF distribution which is not uniform according to the device's distance to the GW, as seen in Figure 6.4(d).



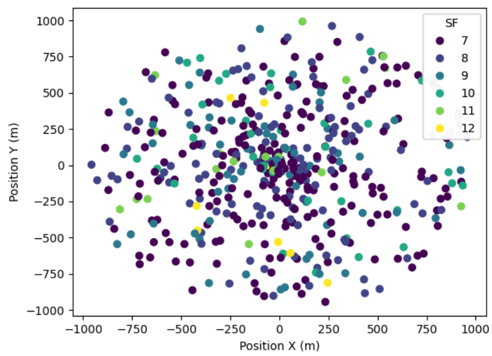
(a) ADR.



(b) EXPLoRa-SF.



(c) EXPLoRa-AT.



(d) BLO.

Figure 6.4: Allocation of SF for 500 EDs using the four different algorithms.

6.5 Battery Consumption analysis

Figure 6.5 shows the minimum battery level (in %) over all 500 devices, after each round for each SF allocation method. Again, the 500 devices are distributed in a circle of 1000 m radius around the GW. All devices are within range and transmit one message per minute. The device's battery capacity is 500 mAh. Each simulation round lasts one hour, meaning that after 60 transmissions the SF allocation methods run again. The total duration of all rounds is 24 hours or 1 day, allowing to infer the expected network lifetime, defined as the time at which the first node of the network runs out of energy. The updated information (mainly battery level and RSSI) is used as input by the algorithms after each round. Thus, the behavior of each method over time can be assessed.

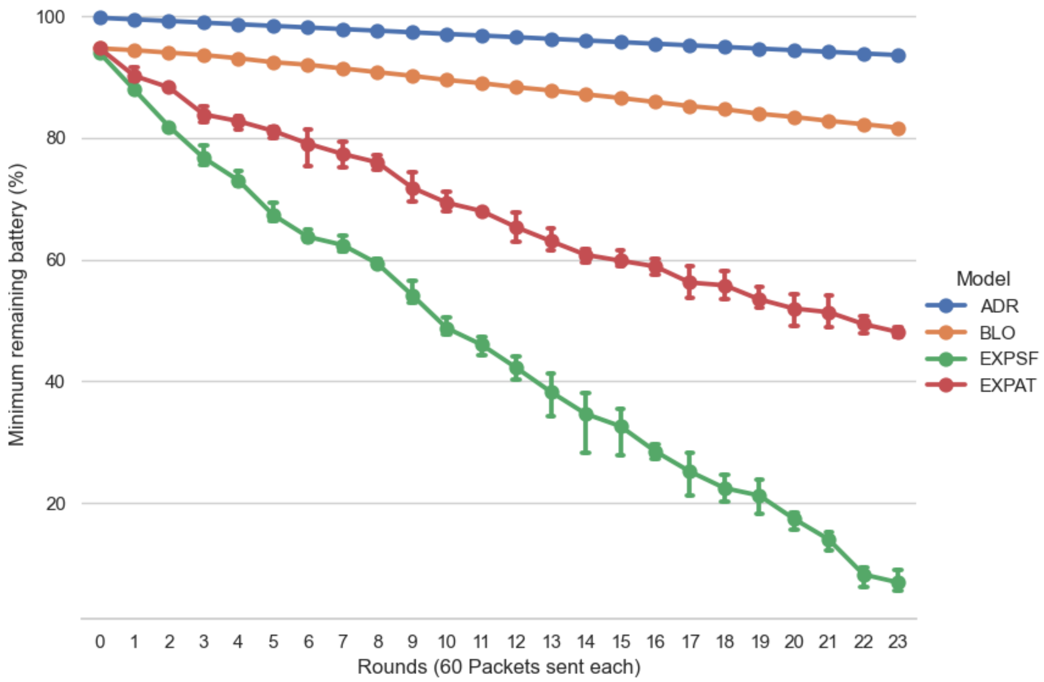


Figure 6.5: Lowest remaining energy as a function of rounds, with 500 EDs transmitting 51-byte packets each 60 s.

Figure 6.5 shows that ADR presents the least steep curve, maintaining a steady battery level superior of 90% after all rounds, indicating minimal energy consumption. This is expected since, as the devices are near the gateway, ADR allocates all of them to SF7 during all the rounds. This produces the highest collision rate and lowest DER. BLO demonstrates great energy efficiency, with the minimum remaining battery gradually decreasing to approximately 85% by the end of 24 rounds. This is explained because BLO divides the EDs into different SF groups and, after each round, the devices with the lowest battery will be assigned to the lowest SF possible, which will spare less battery than with ADR constant SF. However, EXPLoRa-SF and EXPLoRa-AT show more significant energy consumption. They also divide the devices into SF groups, but these proposals ignore remaining battery information and allocate devices to SFs based only on RSSI information, which mainly depends on the distance to the GW. EXPLoRa-SF experiences the steepest decline, with the minimum battery level dropping below 40%, indicating the highest energy demand of all the methods. Similarly, EXPLoRa-AT depletes the battery more rapidly than ADR and BLO, maintaining a minimum battery level slightly above 50% by 24 hours (i.e. 24 rounds). The results that while ADR is the most battery-efficient algorithm. However, as seen later, it may not optimize other network performance metrics. Furthermore, we observe significant increase in network lifetime comparing BLO with SoA strategies, with improvements of 10 and 3.6 times over EXPLoRa-SF and EXPLoRa-AT, respectively.

Finally, we investigate the compromise between energy spent and information successfully transmitted, to assess the algorithms' efficiency. Figure 6.6 shows the energy consumed per successfully received byte, varying the size of the area where EDs are located. Each ED sends one message per minute. Note that regardless of the distance to the GW, all the curves are reasonably stable. The ADR scheme has the lowest energy cost, starting below 5 mWh per byte and increasing only slightly at the maximum distance of 3000 m. This increase is caused because as the EDs moves away from the GW, it's necessary to increase it's SF, consuming more energy. BLO and EXPLoRa-AT consume moderate energy, with BLO maintaining a stable consumption just below 8 mWh per byte, while EXPLoRa-AT averaging around 11 mWh per byte. In contrast, EXPLoRa-SF is the least energy-efficient, with its energy consumption significantly higher, remaining above 25 mWh per byte for all distances. Comparing with the novel approaches, BLO has approximately one third of the cost of the EXPLoRa-SF and 25% less than EXPLoRa-AT. The results suggest that ADR is the most energy-efficient algorithm. Although allocating all devices to the same SF causes a high collision rate, the cost of lower SFs transmissions are multiple times reduced comparing with higher SFs. Therefore, this energy-efficiency presented by ADR generates a trade-off for other metrics, such as improved DER in high-traffic network scenarios, as seen next.

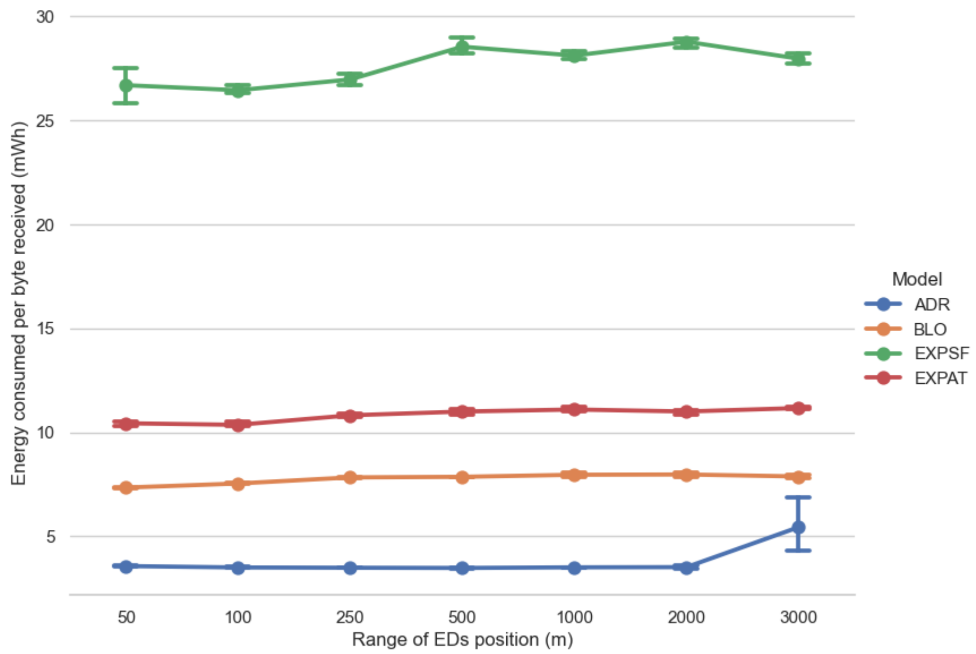


Figure 6.6: Energy cost per byte successfully received as a function of the maximum ED distance from the GW, with 500 EDs and 51-Byte payload.

6.6 Data Extraction Rate analysis

Figure 6.7 shows the variation of the DER as a function of the packet transmission rate (in packets per minute) of devices in a LoRaWAN network, comparing the four SF allocation algorithms. We consider 500 EDs distributed in a maximum range of 1000m from the GW and sending 51-bytes payload. The DER is represented on the vertical axis, while the radius on the horizontal axis represents the increasing of packet rates, from 1 packet per hour (0.017 msg/min) to 1 packet every 10 second (6.0 msg/min). This simulation goal is to compare the scalability of the proposals. At lower packet rates (0.017 msg/min), all algorithms perform nearly perfectly, with DER close to 100%. However, as the packet rate increases, DER declines across all algorithms, indicating the impact of increased traffic and network congestion. ADR experiences the steepest decline, with DER dropping below 20% at the highest packet rate (6.0 msg/min), highlighting its poor ability to handle high traffic because it allocates devices to the lowest SF possible causing several EDs to use the same SF, thereby compromising radio diversity. EXPLoRa-SF performs better than ADR but still suffers significant degradation as the packet rate increases. In contrast, EXPLoRa-AT and BLO maintain higher DER values across all packet rates. Even at a packet rate of 2.0 msg/min, BLO and EXPLoRa-AT maintain DER values above 60%, showcasing their superior efficiency and scalability under heavy traffic. This analysis highlights that BLO and EXPLoRa-AT have the most robust algorithms for handling high device transmission rates in LoRaWAN networks, as both allocate resources fairly considering the equalization of time of transmissions for each SF group. When we compare the performance of BLO with ADR, for the transmission interval of 2 msg/min, BLO has an approximately 50% higher DER. Finally, EXPLoRa-SF performs slightly better for the highest packet rate. This shows that the strategy to allocate devices into different SF groups (i.e., six equal groups) presents the advantage of decreasing the collision rate, even if using a simpler strategy, which ignores energy consumption.

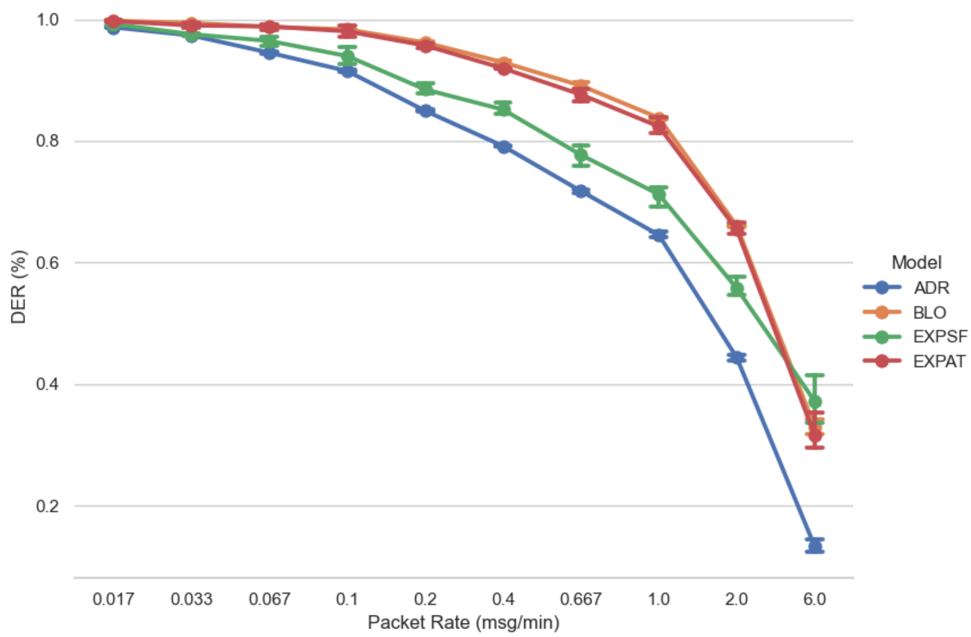


Figure 6.7: DER as a function of packet rate, with 500 EDs and 51-byte packets.

Figure 6.8 illustrates the variation of the Data Extraction Rate (DER) as the size of the area over which EDs are spread varies, comparing the performance of the four Spreading Factor (SF) allocation algorithms, considering a scenario of 500 EDs using 51 bytes transmissions with 60 s of interval. The DER, expressed as a percentage on the vertical axis, reflects the efficiency of data transmission, while the horizontal axis shows the maximum device-to-gateway distance in meters, ranging from 50 to 3000 meters. EXPLoRa-AT and BLO have a similar behavior, both presenting a better overall performance compared with ADR and EXPLoRa-SF, achieving a higher DER across all distances, particularly at shorter ranges where it exceeds 82 5%. EXPLoRa-SF presents a DER of approximately 70% for shorter ranges, and also indicates a higher DER stability with the increase in range but lower efficiency compared to EXPLoRa-AT and BLO. In contrast, ADR consistently underperforms the other approaches, with DER starting below 65% at short distances and improving slightly as the distance grows. Again, we note that ADR produces the lowest DER for close ranges, as it allocates all devices to a single spreading factor (SF7), thereby compromising radio diversity. This restrictive approach leads to a suboptimal utilization of available bandwidth. All algorithms performance gradually declines with increasing distance. This is due to more devices entering a zone due to the need to increase the SF in order to improve the receiver sensitivity, causing more collisions in these higher SFs.

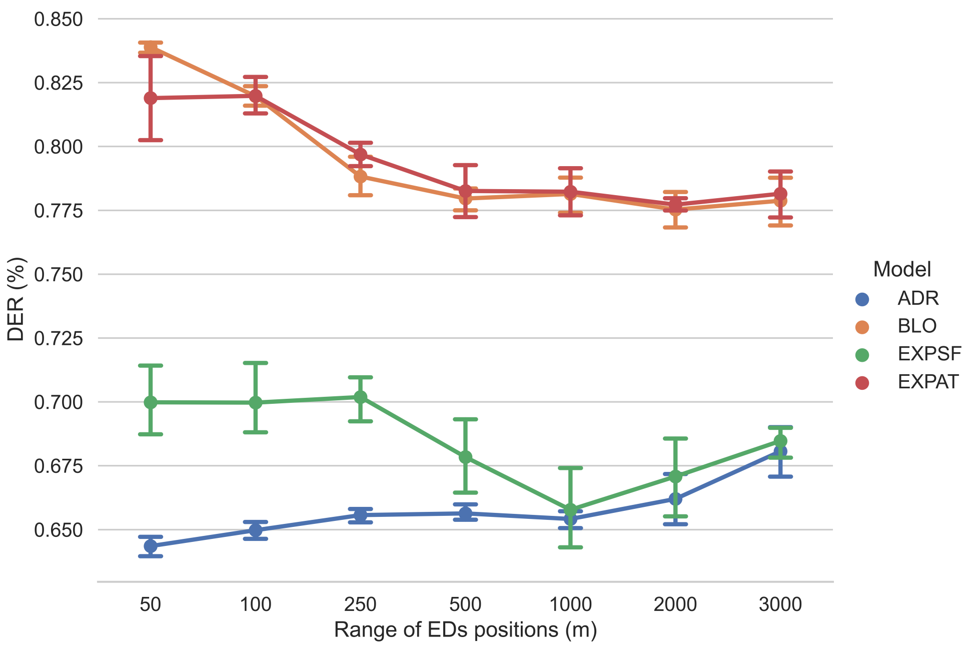


Figure 6.8: DER as a function of the maximum range where EDs are located, with 500 EDs and 51-byte packets.

Figure 6.9 shows the variation of the DER as the number of EDs in a LoRaWAN network increases, comparing the performance of the four SFs allocation algorithms, considering a scenario using 51 bytes transmissions with 60 s of interval. All EDs are in a maximum distance from the GW that allows them to use any SF. At smaller device counts, all proposals achieve high DER values, indicating efficient data extraction in a small network. However, as the number of devices increases, their performance diverges. ADR shows the steepest decline, with DER dropping below 0.6 for networks of 1000 devices, highlighting its poor scalability under high congestion. EXPLoRa-SF performs slightly better than ADR but still suffers a significant drop as the network size grows. In contrast, BLO and EXPLoRa-AT maintain much higher DER values, with BLO demonstrating the best performance overall, followed closely by EXPLoRa-AT. These two algorithms exhibit greater resilience to network congestion, maintaining DER above 0.6 even at 1,000 devices. Comparing the DER of BLO with ADR, BLO shows an increase of up to 55%. This analysis underscores the effectiveness of BLO for large-scale LoRaWAN deployments.

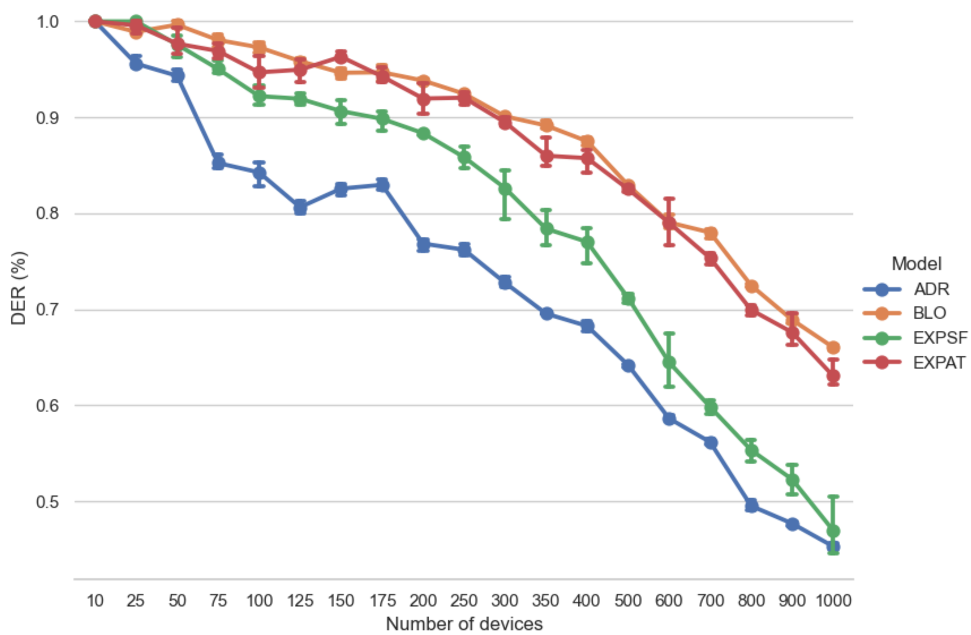


Figure 6.9: DER as a function of the number of EDs, using the four different algorithms.

Chapter 7

Conclusion and Future Work

This dissertation presented a dynamic strategy for optimizing the SF allocation in LoRa networks, named BLO (Battery Life Optimization). The basic concept is to take advantage of the LoRaWAN characteristics of SF's orthogonality, which allows the development of a mechanism to reduce interference among groups of devices which are assigned to different SFs, and consequently improve network capacity. Therefore, BLO key idea is to periodically group EDs into SF groups based on their current battery levels, minimizing collisions within these groups, improving the data extraction rate and fairness in energy consumption among the network. The periodic reallocation ensures a fair distribution of battery consumption across the EDs, that is reached as we use the current battery percentage under consideration to perform the SF allocation, so that devices with less remaining energy uses the lowest possible SF, which minimize energy consumption.

The BLO strategy was compared with state-of-the-art SF allocation methods, using the NS-3 network simulation tool. We present the results of the BLO proposal and other three solutions: ADR, EXPLoRa-SF, and EXPLoRa-AT. BLO produces the best performance overall regarding the majority of analysis evaluating the Data Extraction Rate (DER) and fairness in energy consumption when varying several parameters, such as the number of devices and transmission interval.

Simulations reveal that BLO outperforms the default LoRaWAN ADR in all cases regarding the evaluations over the DER, especially under high traffic conditions when it achieves a remarkable 55% increase in successful message delivery rates. The main reason for this is that the ADR mechanism does not consider the overall performance of the network for SF allocation, causing this proposal to have poor ability to handle high traffic because it allocates devices to the lowest SF possible, only considering it's RSSI and SNR, causing several EDs to use the same SF, thereby compromising radio diversity. The simulations highlight BLO as the most efficient algorithm for handling high device transmission rates in LoRaWAN networks, as it allocates resources fairly considering the equalization of time of transmissions for each SF group, showing the effectiveness of BLO for large-scale LoRaWAN deployments.

Additionally, BLO outperforms both EXPLoRa-SF and EXPLoRa-AT in terms of energy consumption, resulting on extended network lifetime, with improvements comparing BLO with SoA strategies, with improvements of 10 and 3.6 times over EXPLoRa-SF and EXPLoRa-AT, respectively. Both EXPLoRa methods also divide the devices into SF groups, but these proposals ignore remaining battery information and allocate devices to SFs based only on RSSI information.

The integration of the proposed BLO scheme in a LoRaWAN network is simple and does not require modifications to the protocol or any information which is not already available at the NS, which makes our proposal feasible to implement in LoRaWAN networks.

Future research should consider a wider range of applications using the same network with different transmission intervals, mobility pattern and environmental factors. Also, one important analysis to be done in the future is about the impact of transmission power control over the network lifetime. Also, regarding the power consumption measures, we can analyze the impact of other components presented in the device circuit, such as the voltage regulator. Finally, subsequent analysis will be dedicated to multi-gateways scenarios, as in this dissertation we have considered a single GW.

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