Universidade de Aveiro
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Medium access control in LoRa networks with multiple low-cost gateways

Acesso ao meio em redes LoRa com múltiplas gateways de baixo custo

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Doutor Nuno Miguel Abreu Luís, Professor Adjunto do Instituto Superior de Engenharia de Lisboa e co-orientação científica do Doutor André Ventura da Cruz Marnôto Zúquete, Professor Auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro

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Palavras-chave

LoRa, Low Power Wide Area Networks, Internet of Things, Protocolo de Controlo de Acesso ao Meio, Redes de Larga Escala, Redes com Múltiplas Gateways, Canal Único

Resumo

Com o aparecimento das tecnologias Low Power Wide Area Network (LPWAN), como suporte para as aplicações da Internet of Things (IoT), Long-Range (LoRa) tornou-se popular, sendo atualmente uma das tecnologias LPWAN mais promissoras, ainda que as suas transmissões tenham baixas taxas de débito e restrições nos ciclos de trabalho. A popularidade deve-se às características que a tecnologia LoRa possui adequadas para redes IoT de larga escala, que vão desde transmissões de longo alcance, garantidas pelo esquema de modulação que esta utiliza, até ao baixo consumo de energia, aspeto crucial em redes de sensores da IoT.

O foco desta dissertação é o estudo de estratégias de controlo de acesso ao meio para redes LoRa de grande escala com canal único e múltiplas gateways, relativamente à quantidade de informação útil entregue e à justiça no acesso ao meio.

Inicialmente, é proposto e analisado um esquema de controlo de acesso ao meio para redes LoRa com múltiplas gateways e com um único canal, onde os mesmos parâmetros de transmissão são utilizados por toda a rede. Este é baseado no protocolo ALOHA puro utilizado no LoRa, e cada nó terminal utiliza pacotes de controlo para anunciar as suas transmissões.

No seguimento, é proposto uma nova estratégia de acesso ao meio baseado na alteração do canal de transmissão. Neste, cada nó terminal usa as características de transmissão que lhe forem mais favoráveis, relativamente à qualidade de sinal que tem com as gateways que se encontram no seu alcance de comunicação.

Estas estratégias visaram aumentar a eficiência da rede, permitindo que os nós terminais transmitam mais rapidamente, e aumentando a percentagem de pacotes transmitidos com sucesso através da redução da quantidade de colisões, possibilitada pela regulação da competição no acesso ao canal de transmissão.

Keywords

LoRa, Low Power Wide Area Networks, Internet of Things, Medium Access Control Protocol, Large Scale Networks, Multiple Gateway Network, Single-channel

Abstract

With the emergence of Low Power Wide Area Network (LPWAN) technologies, as support to Internet of Things (IoT) applications, Long-Range (LoRa) popularity emerged, being actually one of the most up-and-coming LPWAN technologies, despite the low-rate transmissions and duty-cycle restrictions. Such recognition is due to LoRa's suitable characteristics for large-scale IoT networks, which span from long-range communications, guaranteed by its proprietary modulation scheme, to low power consumption, a fundamental feature for IoT sensor networks.

The focus of this dissertation is the study of medium access control strategies in large-scale single-channel LoRa networks with multiple gateways with respect to the amount of delivered useful information and network access fairness.

Firstly, it is proposed and analysed a medium access control strategy for LoRa networks with multiple single-channel gateways and the same transmission parameters are used by the entire network. It is based on the pure-ALOHA protocol used in LoRa, and each end-device uses control packets to advertise its transmissions.

In the following, a new access strategy based on channel hopping is proposed. In this, each ED uses the transmission characteristics that are most convenient to it, with respect to the signal's quality with the single-channel GWs that are in its communication range.

These strategies aimed to increase the efficiency of the network, allowing end-devices to transmit faster and increasing the percentage of successfully transmitted packets by reducing the amount of collisions, given the regulation of the competition in the access to he transmission medium.

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Acronyms

3GPP 3rd Generation Partnership Project. 7, 8

ACK Acknowledgment. 12, 18, 21, 29

AD MAIORA ADaptative Mitigation of the AIr-time pressure in lORA. 21, 23

ADR Adaptive Data Rate. 10, 12, 19–23

AES Advanced Encryption Standard. 12

BER Bit Error Rate. 15, 21, 23

bps bit per second. 8

BPSK Binary Phase Shift Keying. 8

BS Backoff Slots. 34–37, 49, 74

BW Bandwidth. 12, 13, 52

CF Carrier Frequency. 12, 13

CH-IC Channel Hopping - Ideal Channel. ii, v, 46–49, 53–55, 57

CH-MIC Channel Hopping - Most Ideal Channel. ii, v, 46–49, 52–56

CH-MICF Channel Hopping - Most Ideal Channel Filtering. ii, v–vii, 46, 48, 49, 52–55, 60, 61, 63, 66, 69–72, 74, 75, 78, 79

CM Change Mode. v, 40–43, 46, 51, 52

CR Coding Rate. 11–14, 52

CRC Cyclic Redundancy Check. 14

CSMA Carrier Sense Multiple Access. 16

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance. 9, 17

CSS Chirp Spread Spectrum. 10, 11

CTS Clear To Send. i, v, 17, 18

D7AP DASH7 Alliance Protocol. 9

dB decibel. 11, 52

dBm decibel miliwatt. 6, 13, 50

DER Data Extraction Rate. 15, 19

DWGA Dynamic Weighted Greedy Algorithm. 21, 23

ED End-Device. ii, v–vii, ix, 1, 2, 5–7, 9–12, 14, 15, 18–23, 25–75, 77–79

ELA Enhanced Link Adaptation. 21–23

FADR Fair Adaptive Data Rate. 20, 23

FEC Forward Error Correction. 11, 13, 14

FSK Frequency Shift Keying. 11

FUOTA Firmware Updates Over The Air. 10

GPRS General Packet Radio Service. 8

GSM Global System for Mobile Communications. 8

GW Gateway. i, ii, v–vii, ix, 1, 2, 6–12, 14, 15, 18–23, 25–28, 30, 32–34, 36, 37, 39–43, 45–74, 77, 78

Hz Hertz. 6–9, 13, 52

IEEE Institute of Electrical and Electronics Engineers. 12, 17

IoT Internet of Things. 1, 5, 6, 8, 11, 12, 14, 20, 22, 77

ISM Industrial, Scientific and Medical. 6, 7, 9

ISO/IEC International Organization for Standardization / International Electrotechnical Commission. 9

JFI Jain's Fairness Index. vi, ix, 15, 34, 56, 73

kbps kilobit per second. 8

LoRa Long-Range. v, vi, 1–3, 5, 6, 8–14, 17–23, 25–30, 32–35, 39, 40, 46, 50, 64, 75, 77

LoRaWAN Long Range Wide Area Network. i, v, 2, 9, 10, 14, 20, 22, 25, 77

LPWAN Low-Power Wide Area Network. i, 1, 2, 5–10, 22

LTE Long Term Evolution. 7, 8

LTE-M Long Term Evolution for Machines. 5, 7, 8

MAC Medium Access Control. i, 5, 7, 9, 10, 15–17, 22, 25, 39, 49, 77, 78

NAK Negative Acknowledgment. 21

NAV Network Allocation Vector. i, v, 17, 18

NB-IoT Narrow-band IoT. 5–8

OFDM Orthogonal Frequency Division Multiplexing. 8

OGA Original Greedy Algorithm. 21, 23

OSI Open System Interconnection. 15

PCR Packet Collision Rate. 15, 21, 23

PDR Packet Delivery Ratio. 19, 22, 23

PER Packet Error Rate. 15, 20, 21, 23

PHY Physical Layer. 9, 10

REDER REtransmission Data Extraction Rate. 19

RFID Radio Frequency Identifiers. 5, 9

ROC Reliability Of Connections. 21

RSSI Receive Signal Strength Indicator. ix, 13, 19–23, 26, 27, 34, 36, 39, 41, 50

RTS Request To Send / Ready to Send. i, ii, v–vii, 17, 18, 26–32, 34–37, 41–43, 46–50, 52–60, 62–71, 74–79

RTSFU Real-Time SF Upgrade. 19, 23

SC-FDMA Single Carrier Frequency Division Multiple Access. 8

SF Spreading Factor. xiii, 12, 13, 19–23, 40, 52

SIFS Short Interference Space. 18

SNR Signal-to-Noise Ratio. 13

TDMA Time Division Multiple Access. iii, 16, 63, 74–76

ToA Time on Air. ix, 12, 13, 19–21, 23, 25–28, 30, 40, 43, 47, 51, 52

TP Transmission Power. 12, 13

UNB Ultra Narrow Band. 8, 9

Wi-Fi Wireless Fidelity. 5, 6

WSAN Wireless Sensor and Actuator Network. 9

WSN Wireless Sensor Networks. i, 5, 16, 17, 22

Chapter 1

Introduction

1.1 Context and Motivation

The adoption of Internet of Things (IoT) applications is growing year after year due to the emergence of low power wireless technologies [6, 5, 40]. With the main objectives focused on network efficiency, low power consumption and long-range transmissions, the applicability of IoT extends from Smart Cities, Smart Homes and efficient transport systems to industrial and medical applications, allowing, for example, the proper monitoring of patients' health and activities [9], not only in hospital environment but also in their everyday life, increasing the level of supervision. Due to this wide range of applications, it is expected that the number of connected IoT devices will have a fast growth during this decade. More specifically, it is estimated that connected IoT devices will grow from 7 billion in 2017 up to 20 billion in 2023, corresponding to a growth of about 19% per year [36] and, according to IHS Markit, the market of IoT will include around 75.4 billion of connected devices in 2025. This represents an annual growth of about 89% between 2023 and 2025, considering both studies.

Low-Power Wide Area Network (LPWAN) technologies have emerged in recent years to support IoT applications due to their characteristics designed to provide wide-area and massive scale connectivity, in exchange for low power, low cost and low data rates, for both End-Device (ED) and infrastructure. Amongst them, Long-Range (LoRa) is one of the most popular and interesting ones, thanks to its robustness to noise, which enables long-range transmissions, the non-destructive property of colliding packets and also its power efficiency.

This dissertation will focus on large-scale LoRa networks with multiple, single-channel Gateways (GWs), due to its lower price compared to GWs capable of operating over multiple channels simultaneously. The use of single-channel LoRa GWs raises problems, as they are not capable, unlike those with multiple channels, of decoding simultaneous orthogonal transmissions. That way, the device is only allowed to transmit one packet at a time to each GW. If there are two simultaneous transmissions taking place, they will collide. Consequently, only one of them, at most, will be correctly decoded, thanks to the LoRa's non-destructive property. In addition, the channel on which each ED transmits, if it is not the most appropriate, may spend unnecessary power and time, two factors of extreme importance in low constrained devices. Additionally, it should be highlighted that while operating in the 868MHz unlicensed frequency band, each transmission is restricted to a 1% duty-cycle, and then the shorter the time spent on transmitting, the less is the mandatory backoff and more packets can be transmitted.

1.2 Objectives

In order to solve the problems presented above, this dissertation aims to develop a medium access strategy for large-scale LoRa networks with multiple, single-channel GWs capable of managing the network transmissions, looking for the lowest packet loss, while managing the operating parameters of both GWs and EDs. For that, the strategy has to change such parameters over time, so that each ED transmits its packets in a more efficient way, spending the least possible time and power appropriate to its condition of communication with a GW, or GWs, of interest. Allied to this, it is also sought that the access strategy does not affect the network fairness, allowing the same transmission opportunities to all EDs, even those with a bad connection with the GWs, that could remain some time without transmitting due to the competition.

1.3 Contributions

This dissertation has accomplished the following:

- Development of a medium access strategy, based on the pure-ALOHA, that manages large-scale networks with multiple, single-channel GWs using control packets to warn about future transmissions, so as to reduce the collisions and improve the performance of the network GWs, whose transmission parameters are the same for all of them and dot not change over time;
- Development of a channel hopping protocol where the EDs transmit using their most appropriate channel, improving the efficiency of each transmission, regarding the transmission rate and the power consumption;
- Development of Matlab simulators that follow the behavior of each protocol studied, used to evaluate their performance;
- A study on the influence that the overlap formed by the coverage of multiple GWs has on the overall performance of a LoRa network;
- A study on the trade-off between the increasing of the number of single-channel GWs in the network and the increasing of the complexity of the medium access protocol used, in order to obtain the best network performance.

1.4 Document Organization

The remaining document is organized as follows:

- **Chapter 2** introduces the state of the art regarding LPWANs and presents related work regarding the subject of the dissertation;
- **Chapter 3** presents and evaluates an alternative strategy to the pure-ALOHA, used by LoRaWAN, that uses control packets, for large-scale LoRa networks with multiple single-channel GWs;

- **Chapter 4** proposes and evaluates an access strategy for large-scale LoRa networks that builds upon the previous one now using adaptive transmissions that can benefit from different communication parameters (which broadly define a communication channel);
- **Chapter 5** gives a supplementary evaluation of the proposed access strategies, considering different network scenarios;
- **Chapter 6** concludes the dissertation, giving new lines of study for possible works to be performed in the future.

Chapter 2

State of the Art

This chapter provides to the reader critical concepts for the correct understanding of the work developed in this dissertation, as well as the related work. Section 2.1 introduces the LPWANs, presenting the main features that make them suitable to be used in IoT applications, and also some of the different technologies used in this type of networks. As this dissertation is about LoRa networks, focus is given on this technology. Section 2.2 presents the performance parameters used in this thesis. Section 2.3 addresses the Medium Access Control (MAC) protocols, their traditional families and different classes when applied to Wireless Sensor Networks (WSN), as LoRa networks could be themselves sensor networks and so, share the same concerns. Lastly, Section 2.4 overviews the related work with respect to this dissertation, focusing on LoRa networks, aiming to improve the power consumption, goodput or even the fairness of the network, addressing both single and multi-gateway scenarios. Section 2.5 concludes the chapter.

2.1 Low Power Wide-Area Networks

The rise of the IoT applications, applied to a wide range of situations, led to the emergence of LPWAN technologies, as they have characteristics that are suitable to their requirements. Therefore, in order to satisfy the wide range of different IoT applications, with specific requirements, several technologies have emerged. These technologies can be divided in sub-groups [31, 18], according with their applicability:

- **Very Short-Range Wireless Peer-to-Peer Communication**: e.g., *Radio Frequency Identifiers (RFID)*;
- **Short-Range Wireless Networks**: e.g., *Bluetooth*, *ZigBee*, *Z-Wave*;
- **Wireless Local Area Networks**: e.g., *Wi-Fi*;
- **Cellular Networks**: e.g., *NB-IoT,LTE-M.*

The wireless technologies started by being the ones in the dominant position in the IoT market, thanks to their easy-to-use protocols. However, since they provide a very limited range of communication, their usage in IoT also became limited. In fact, the range of communications has become, right after the power consumption of the End-Devices (EDs), the most critical aspect of most IoT applications. Therefore, the rise of the LPWANs took place and brought much more advantageous solutions for this type of applications where one of the biggest concerns is the communication reach.

So, LPWANs are a category of wireless communication technologies that were originally designed to support IoT deployments, acting as a complement not only to the cellular but also to the other existing wireless technologies. Thus, they are designed to provide wide-area and massive scale connectivity, in exchange for low power, low cost and low data rates, for both devices and infrastructure [5, 18]. All these characteristics made LPWAN technologies highly requested, and several technologies were developed, such as *DASH7*, *Weightless-N*, *Weightless-P*, *SNOW*, *SigFox*, *Ingenu*, *NB-IoT* and *LoRa* [33].

While the cellular-based LPWANs operate in the licensed band, non-cellular operate in the unlicensed sub-GHz Industrial, Scientific and Medical (ISM) band [5]. Operating in the sub-GHz ISM band guarantees two major advantages to the network: less congestion than in the 2.4 and 5 GHz bands, usually used by wireless technologies such as *Wi-Fi*, and also it is free. However, some limits must be respected, such as duty-cycle requirements of each transmission, in order to allow the coexistence of a large number of devices, and the transmission power of the devices, limited to 14 dBm [15].

LPWAN technologies are considered one of the key technologies to the future of IoT. There are already some interesting ones, however, they are still in a very initial stage of they existence.

2.1.1 Characteristics

LPWAN technologies [16, 22, 5] present, as referred before, characteristics that enhance the capabilities of more and more IoT applications, which makes them the preferred ones. The most important characteristics are described in more detail below.

2.1.1.1 Long-Range Connectivity

As most of non-cellular LPWANs operate in the unlicensed sub-GHz ISM band, they are able to provide longer range communications as they have better propagation characteristics, thanks to the low frequency signals. In fact, the propagation range spans from a few kilometers in urban areas, where the signals are in the presence of a greater quantity of obstacles, such as tall buildings, to tens of kilometers in rural areas, where there is a lower to none density of them [18, 31]. So, the use of narrow band channels is requested, in order to decrease the noise level.

2.1.1.2 Low-Power

To achieve a longer operation time with the same battery, the IoT devices, hereinafter referred as EDs (End-Devices), have to consume a very low power throughout its execution. To do so, the EDs communicate directly with the network Gateways, hereinafter referred as GWs, as the LPWANs form a star topology that allows it to be done. Therefore, all the extra energy consumed in eventual multi-hopping operations, for example, is eliminated.

2.1.1.3 Low Deployment and Operation Cost

Instead of requiring a complex and expensive infrastructure and the use of licensed bands, the non-cellular LPWANs provide an outstanding alternative to it, as they use the unlicensed sub-GHz ISM band, and a simple and inexpensive infrastructure to be deployed.

So, these two important characteristics, easy deployment and low cost contributed to the rise of the LPWANs as a communication solution.

2.1.1.4 Reliability and Robustness

Other aspects of major importance are the robust modulation and spread-spectrum techniques that are used in the communication, capable of guaranteeing not only a better signal resistance to interference but also an increased level of security of the transmissions, supporting a simple cryptography method where the devices and network share a secret key [18]. So, the resistance to interference is assured because of the used spread-spectrum techniques, as said, and the narrow-band signal is spread all over the frequency domain, with lower power density. Therefore, even if a given frequency suffers interference, as the signal is spread, the signal losses are much less alarming as if the narrow-band signal was not spread and so, for the same frequency, the losses would be considerable.

2.1.1.5 Potential to Scale

The support for a massive number of EDs is guaranteed by the use of narrow-band, that uses the limited bandwidth available efficiently, and the avoidance of a multi-hop topology that could reduce the potential to scale. This reduction would be due to the power that each ED would use to relay received packets that will increase with the number of EDs in the network. Furthermore, some LPWANs choose to use multiple antennas to enable the GWs to support a larger number of EDs, whilst others opt to use parallel communications using a single antenna, through different channels, so there are no collisions. One way or another, it provides scalability to the network. The major drawbacks that affect the scalability of LPWANs are the duty-cycle requirements, imposed by the unlicensed band where they work, the reliability requirement and also the underlying MAC protocol.

2.1.2 Technologies

As referred before, several LPWAN technologies are being developed to perform long distance and low-power wireless communications, since conventional technologies do not allow it. They can be divided into two classes based on their working frequency band, which can be licensed or unlicensed [21].

2.1.2.1 LPWAN technologies on licensed bands

In this section we present some developed LPWAN technologies that use the licensed band of the spectrum, namely Narrow-band IoT and LTE-M, two of the most used technologies of this family.

Narrow-band IoT

Narrow-band IoT (NB-IoT) [28], also known as LTE Cat NB1, is an LPWAN technology announced around June 2016 as part of Release 13 of 3rd Generation Partnership Project (3GPP). It aims to provide long battery life, low device cost, as well as low complexity and flexibility of the deployment, guaranteed by the use of only a small portion of the available spectrum and extension of signal coverage for IoT applications. It supports up to fifty thousand devices per cell and demands a minimum bandwidth of 1.80×10^2 kHz , in order to establish communication.

Although not compatible with 3G, it can coexist with GSM, GPRS and LTE, and, with a single upgrade on top of the existing LTE infrastructure, it can be supported. Regarding the deployment, it can be done with one of the three following options:

- ***in-band***, inside a single LTE physical resource block of 1.80×10^2 kHz;
- ***guard-band***, inside an LTE guard-band, taking advantage of unused bandwidth;
- ***stand alone***, inside a single carrier of GSM of 2.00×10^2 kHz, using underused bandwidth.

Regarding the modulation, NB-IoT uses Orthogonal Frequency Division Multiplexing (OFDM) modulation for downlink communications and Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink communications. The major advantage of these modulations is based on the fact that a single cell can handle billions of connections and thus, serve from 100 up to 50 thousand devices, providing scalability to the network.

It limits the bandwidth to a single narrow-band of 2.00×10^2 kHz, the data rate to 2.50×10^2 kbps for the multi-tone downlink communication and the single-tone uplink communication to 2.0×10^1 kbps.

LTE-M

Long Term Evolution for Machines, also known as LTE-M [14], is an evolution of the LTE standard, standardised by 3GPP in the Release 13 specification. While respecting the essential structures of standard LTE systems, it decreases the power consumption and the deployment cost relatively to the standard version of LTE, being more suitable to IoT applications. Thus, this technology searches for backward compatibility with standard LTE and for a maximization on the reuse of the already existing cellular infrastructures.

2.1.2.2 LPWAN technologies on unlicensed spectrum

This section overviews some LPWAN technologies that use the unlicensed band, a frequency band that can be used for free, namely Ultra Narrow Band, SigFox, DASH7 and LoRa.

Ultra Narrow Band

The Ultra Narrow Band (UNB) technology [27] was designed by the SigFox company in 2009. Its main goal is to ensure universal connectivity for large-scale IoT networks requiring low-power consumption. To do so, it uses Binary Phase Shift Keying (BPSK) modulation for the connection to the GWs over ultra-narrow band, with a typical value of bandwidth equals to 1.00×10^2 Hz. Although it uses very cheap antennas and high receiver sensitivity, its data rates can only reach 1.00×10^2 bps [21].

SigFox

SigFox [25] is a proprietary LPWAN technology based on the UNB modulation technique, discussed earlier. Hence, it offers an efficient spectrum utilization that provides an increase of the network goodput, allowing a reduced power consumption.

It uses duty-cycled transmissions of 1% in Europe and supports low data rate, compared to other LPWANs. Therefore, each element of the network is able to send over the uplink up to 140 12-byte messages per day, respecting the duty-cycle regulations required when using the license-free bands.

To provide reliable transmissions, SigFox transmits the messages multiple times, resulting in an increase of the energy consumption per unique data packet.

DASH7

The DASH7 Alliance [4] is an industry consortium that defined a full vertical network stack for low power wide area connectivity known as DASH7 Alliance Protocol (D7AP). The D7AP is an open source active RFID standard for bi-directional Wireless Sensor and Actuator Network (WSAN) applications. It complies with the ISO/IEC 180000-7 standard, which is an open standard for the license-free 4.33×10^2 MHz ISM band air-interference for wireless communications. This frequency guarantees to D7A a mid-range propagation up to 2 Km and better penetration capability. Also, offers low power consumption and low latency for connected moving objects, such as low-power sensors and actuators.

DASH7 is named **BLAST** networking technology due to the D7A features:

- ***B**ursty*: Transmit short and sporadic sequences of data;
- ***L**ight*: Packets are limited to 256 bytes;
- **A**synchronous: There is no periodic synchronization, the communication is command response based;
- ***S**tealth*: The GW that receives the data from the ED is pre-approved;
- ***T**ransitive*: An ED is able to move between the range of different GWs.

Regarding to the channel access, to perform uplink communications DASH7 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method while the downlink uses the scan automation process [5].

DASH7 also defined a complete network stack, enabling application and EDs to communicate with each other without the concern of having to deal with the physical or MAC layers. It also supports forward error correction and symmetric key cryptography, to improve the connection confidentiality and authenticity of the communications.

2.1.3 Long-Range

Long Range [18, 33, 21, 2, 37], LoRa for short, is a proprietary Physical Layer (PHY) design used in LoRaWAN specifications. Designed and commercialized by Semtech Corporation, LoRa is the most popular technology used among LPWANs operating on unlicensed bands below 1 GHz. Its implementation is very simple and offers to the consumer very low maintenance and setup cost. According to the 2019 Annual Report of LoRa Alliance [34], the LoRa Alliance continued to strongly differentiate itself from the other technologies and helped raise awareness of where LPWAN technology fits in the broader communications landscape.

2.1.3.1 Network Architecture

Originally, LoRa [13, 5] was only a PHY, providing long-range communication links. Later, it was extended by adding a MAC layer, LoRaWAN, standardized and open sourced by the LoRa Alliance. Some of the main aspects that differentiate LoRaWAN are [34]:

- Firmware Updates Over The Air (FUOTA) that allow devices to be updated remotely, even if they are in remote and hard to reach locations. This enables the evolution of the EDs over their life time, wherever they are;
- Open-source protocol, based on industry collaboration, allowing the permanent development of a technology for the future;
- Quantity of deployed EDs around the globe, being nowadays the most deployed LPWAN technology;
- Different network deployments according to the target applications.

So, LoRaWAN defines the network architecture, as well as a communication protocol and the Adaptive Data Rate (ADR) mechanism [17] that configure the EDs of the network. LoRaWAN uses a special star topology, called star-of-stars topology, where the GWs relay messages between the EDs and a Central Network Server, as Figure 2.1 shows. To do so, it uses a special Chirp Spread Spectrum (CSS) technique.

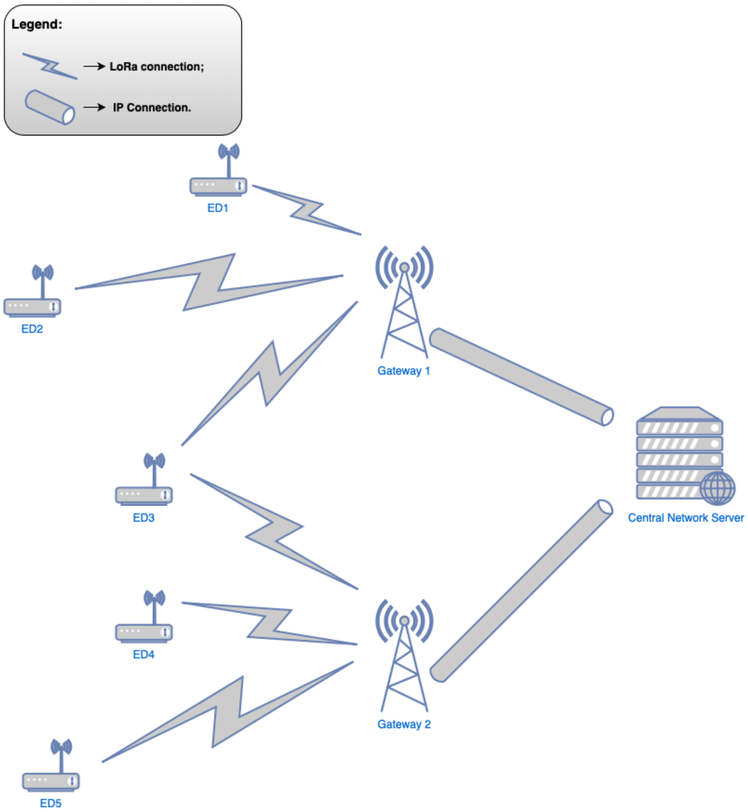


Figure 2.1: Star-of-Stars Network Architecture of LoRaWAN.

In the following, are presented some of the typical elements of the network:

End-Devices: These are devices like sensors, detectors, actuators, where sensing and controlling takes place. They send data packets directly to the GWs, that are in their reach of communication, as long as both are operating using the same parameters, which will be addressed later in this dissertation. Contrarily to what happens in other technologies, in LoRa there are no unicast links between the EDs and the GWs. Every ED transmission can be received by any GW of the network. From the GW they can also receive data packets for synchronization purposes, for example.

Gateways: They forward messages from the EDs to the Central Network Server, and vice-versa. More than one GW can receive the same message from one specific ED and forward it to the Central Network Server.

Central Network Server: It is where all the intelligence of the network lies in. It monitors the GWs and EDs, aggregates the incoming data from the GWs, removes duplicates caused by the forwarding of the same information from various GWs, and also routes or forwards incoming messages to the corresponding application servers.

Actually, there are two categories of LoRa networks: ***co-frequency networks*** and ***differ-frequency networks***. Regarding to the ***co-frequency networks***, both the EDs and GWs use the same frequency band for both uplink and downlink and thus, its capacity and efficiency are limited. In the ***differ-frequency networks***, the capacity and efficiency of the network are enhanced because the EDs and GWs use different uplink and downlink frequencies. In the later case, the EDs and GWs are duplex, while in the other one were simplex. Despite this, due to the use of more frequency bands, the EDs are commonly less sensitive.

2.1.3.2 Features

Let us now overview the main features of the LoRa networks.

Long Range: The long range provided by LoRa is guaranteed by the use of CSS modulation. This technology, originally used in military and space communications, due to its robustness, long-range capacity and low-power requirements, is now used in LoRa communications. Chirp is a signal whose frequency increases, *up-chirp*, or decrease, *down-chirp*, with time. This ensures the phase continuity between different chirp symbols in the preamble part of the physical layer packet, providing a simpler and more effective timing and frequency synchronization between the transmitter and the receiver. A LoRa receiver is able to decode transmissions 1.95×10^1 dB below the noise level, allowing very long communication distances or communications through a great quantity of physical obstacles that cause signal attenuation [8].

It is known that most of the technologies used for IoT connectivity use Frequency Shift Keying (FSK) modulation. When the data rate of the transmission signal is equivalent to four times the data rate of a FSK signal, the sensitivity of LoRa is similar or equal, enabling LoRa to cover more distance than any other technique. Along with this, the Forward Error Correction (FEC), a technique that consists of adding redundant bits, is implemented. The quantity of redundant bits that are added can be changed by manipulating the Coding Rate (CR) value, which will be addressed later in this work.

Battery lifetime: Being one of the most essential requirements of IoT devices, LoRa optimizes it by using an asynchronous communication: EDs only communicate when they have data to send, adopting the ALOHA access scheme. In case the correct delivery of each data packet is confirmed by a packet, an Acknowledgment (ACK) packet, for instance, if this packet is received by a given ED that sent a packet it means that it was correctly delivered. Thus, the ED is able to send another data packet in the next transmission. Otherwise, if the ACK packet is not received by it, the same data packet is re-transmitted, affecting the power consumption of the concerned ED, as the same data packet spends extra power to be re-transmitted. Despite that, the lifetime of the EDs in LoRa networks is greater than in the other technologies that adopt synchronous communications. In fact, according to recent studies, LoRa technology is four to five times better than any other existing technology relatively to power consumption [13].

Network Capacity: Every GW of the network must receive data packets from a large number of EDs and so, they must have an adaptive data rate and multi-channel transceiver. To do so, LoRa uses ADR, a mechanism that optimizes data rate and also, air-time and energy consumption in the network. It is the network that manages the data rates used by every ED according with the transmission statistics from each one of them. Thus, the network can decide if it can change the data rate or the transmission power in order to optimize the use of the resources of the network, using values of Time on Air (ToA) and transmission power concordant to the specifications of the transmission.

Security: Regarding confidentiality and authentication, LoRa uses AES encryption and IEEE 802.15.4/2006 Annex B [13]. Whilst several technologies use only one layer of security, LoRa uses two layers: the network security, that is used to authenticate EDs, and the application security, that is used to protect the application data from the network operators.

Customization of parameters: Due to the higher diversity of IoT applications, it is possible to adapt some parameters according to the application and thus, to optimize the LoRa modulation. Typically, there are five configuration parameters: Carrier Frequency (CF), Spreading Factor (SF), Bandwidth (BW), CR and Transmission Power (TP). By choosing these parameters, we can modify the transmission range, power consumption and the resistance to noise. An explanation of each parameter is presented in the following:

- **Carrier Frequency (CF)**: Center frequency used for transmission. It depends on the transceiver used.

- **Spreading Factor (SF)**: Defines the trade-off between the data rate and the communication range, determining the duration of the chirp. Thus, in LoRa, the SF is the base 2 logarithm of the number of chirps per symbol, given by:

  $$2^{\mathrm{SF}} = \frac{\text{chirp rate}}{\text{symbol rate}}$$

  So, every LoRa symbol is constituted by 2^{SF} chips, which are distributed all over the frequency band, and is able to encode SF bits of information. The increase of one in the

SF will reduce the duration of a chirp by half and duplicate the duration of the LoRa symbol.

The SF can have values between 7 and 12. SF7 represents the shortest ToA and highest data rate whilst SF12 represents the longest ToA and the lowest data rate. The later has an higher Signal-to-Noise Ratio (SNR), sensitivity and energy consumption. Due to the orthogonality of signals with different SF values, it is possible to allocate a specific channel for a given SF.

- **Bandwidth (BW)**: Range of frequencies in the transmission band. It has typical values of 1.25×10^2 kHz, 2.50×10^2 kHz and 5.00×10^2 kHz, that represent the chip rate. So, higher BW means higher data rate and shorter ToA, but also lower sensitivity due to the integration of additional noise.
- **Coding Rate (CR)**: The CR determines the rate of the FEC code. So, the higher it is, the greater the protection against interference it provides. However, with the increase of the CR, the ToA of the transmission will also increase and therefore, it is necessary to evaluate carefully the medium that is going to be used, relatively to the level of interference that the transmission will face, to choose the most fitting CR value, without compromising the ToA of the transmission. The CR encodes 4-bit data, with redundancies, into 5, 6, 7 or 8 bits, according to the following:

  $$\mathrm{CR} = \frac{4}{4+n} \quad , \text{with} n \in \{1, 2, 3, 4\} \tag{2.1}$$

  So, the value of this parameter should be chosen based on the level of interference of the channel that is being used, increasing with the interference.
- **Transmission Power (TP)**: Although the theoretical range of TP is between -4 dBm and 2.0×10^1 dBm, most of the time this range is limited from 2 dBm to 2.0×10^1 dBm, in 1 dBm steps. The selection of this parameter influences the communication range, the sensitivity of the signal to external interference and also the power consumption, that increases with TP. Thus, the selection of this parameter must be made carefully so as to be in accordance with the needs of the transmission that will be carried out.

Radios can communicate with each other as long as they maintain the same SF, BW and CF. Regarding to CR, two devices using different values of it can still transmit packet with each other, as the CR is contained in the Header field of the LoRa packet, that will be referred later in this chapter. Different combinations of these parameters will origin different values of useful bit rate of a LoRa transmission (R_b), according to the following equation:

$$R_b = \mathrm{SF} * \frac{\mathrm{CR}}{\frac{2^{\mathrm{SF}}}{\mathrm{BW}}}$$

When two frames using the same parameters overlap in time, a frame collision occurs, leading to frame losses. However, due to the capture effect found in LoRa modulation, if the difference between Receive Signal Strength Indicator (RSSI) of the two colliding frames is higher than a certain threshold, it is possible to recover the one with higher RSSI [29]. Otherwise, the receiver keeps switching between the two signals and, at the end, cannot decode successfully none of them, losing all the information.

2.1.3.3 Packet Structure

LoRa packets start with a Preamble, which begins with a programmable sequence of up-chirp symbols, followed by two chirp symbols which encode a sync word. This sync word depends on the parameters that are being used by the device transmitting the packet. Thus, if both receiver and transmitter are not using the same configuration, as soon as it understands that the sync word does not correspond to its actual operation parameters, the receiver ignores the packet.

Next to the Preamble, there is the Header of the packet. This is optional and it is transmitted always with a CR of $\frac{4}{8}$, regardless of the value of n in (2.1) to specify the FEC. In this field it is indicated the length of the payload, represented in bytes, using only one byte, making the maximum payload length 255 ($2^8 - 1$) bytes, and the Cyclic Redundancy Check (CRC), that allows the receiver to ignore data packets with invalid headers.

After the optional Header, there is the Payload, which can contain from 1 to 255 bytes. At the end of it may be included an optional 16-bit CRC. The CR of both the Payload and the optional CRC is calculated using (2.1), according with the chosen specifications for the FEC. Figure 2.2 shows the LoRa packet structure.

Figure 2.2: LoRa Packet Structure.

2.1.3.4 LoRaWAN Communications

LoRaWAN Alliance specifications [5, 13, 2, 38] define three classes for an ED using an ALOHA-based protocol. This protocol, as referred before, needs no synchronization and devices only communicate when they have data to send. The three classes have different capabilities, in order to cover a wide range of IoT applications, making possible to choose between battery lifetime and network downlink communication latency and throughput.

A single ED can be involved in more than one IoT application and thus, it can switch between classes, wherein class A must be implemented in all EDs, by default. In the following, are presented the three available classes and their respective behavior.

***Bi-directional End Devices (Class A)*:** The most energy efficient, the EDs are most of the time in the sleeping channel. Follows the ALOHA method of communication and thus, whenever EDs have data packets to send, they send them. In case more than one ED send a data packet to the same GW, at the same time, a collision occurs. After every uplink phase, two windows (RX1 and RX2) are opened to receive data with a latency of 1 second for each one. If the downlink requires more data to be sent, it has to wait for the next uplink transmission. Therefore, this class is only for applications that send small data currents and also can delay downlink communications until the next uplink ones.

***Bi-directional EDs with scheduled receive slots (Class B)*:** Class B, in addition to the random receive slots of class A, adds scheduled receive slots. So, the devices listen to incoming messages on regular intervals synchronized with a beacon.

***Bi-directional EDs with maximal receive slots (Class C)*:** In spite of not having latency, due to the continuous listening for incoming messages, there is an increase in the power consumption relatively to the other two classes. Class C is mostly used for real-time applications, where the power is not constrained and the EDs have to be always listening to the medium in order to do not miss any data packet targeting them.

2.2 Performance Parameters

When studying the performance of a network, there are certain parameters that must be taken into account. In the following are presented the ones that are taken into account in this thesis:

- **Goodput**: The rate of useful information sent by the EDs that is successfully decoded by the GWs of the network.
- **Packet Error Rate (PER)**: Ratio of the number of packets that are unsuccessfully received and the total number of packets received. To be considered incorrect, the packet just needs one wrong bit.
- **Bit Error Rate (BER)**: Number of bit error over a period of time.
- **Data Extraction Rate (DER)**: Is the ratio between the received packets and the transmitted ones.
- **Fairness**: Parameter that measures the opportunity that the EDs have to access the channel and send data packets. The metric used in this dissertation to calculate the fairness is called Jain's Fairness Index (JFI) and will be presented in detail in Section 3.3.
- **Latency**: Time of interval between the instant when an action is taken and the instant response to it.
- **Collision**: A collision occurs when two packets, using the same channel, overlap in time. Its occurrence causes a loss of information in the network.
- **Packet Collision Rate (PCR)**: Quantity of packet collisions occurring in a network over a period of time.
- **Starvation**: Occurs when an ED keeps unable to access the channel for too long, without being able to send its packets. With this, the fairness of the network is impaired.

2.3 Medium Access Control

The Medium Access Control (MAC) is a sub-layer of the link layer of the OSI layer model and it is responsible to guarantee that the communications in the network are done properly. Its role is to coordinate the access to the medium that is shared by several EDs at the same time and so, some of them could access at the same exact time to it. Its task is not easy, considering that in wireless networks any two simultaneous transmissions of information will suffer interference, if they are in the range of each other. This interference may cause loss of information that must be solved using retransmission mechanisms, which will influence directly the power consumption of the network devices and the latency of communications.

Thus, in order to optimize the channel access and to reduce interference and collisions, several packet transmission and retransmission methods have been proposed, mechanisms that manage the access to the medium. These are very important to exist, as in Wireless Sensor Networks (WSN), for example. Despite the data load is generally very low, the traffic generated is usually highly directed from many nodes that, without any management, would access to the medium all at the same time, constantly, what would cause a lot of collisions.

2.3.1 Traditional MAC Families

Traditionally, there are two main approaches to control the access to the medium, being them the *Contention-Based* approach, where the nodes that need to use the medium compete with each other and the winner is allowed to access and transmit information through it, and the *Reservation-Based* approach, where there is a schedule that allows the nodes to access and transmit information through the shared wireless medium whenever their turn arrives.

Contention-Based protocols are based on the competition between the nodes that need to use the channel. The two main schemes of this approach are the ALOHA and the Carrier Sense Multiple Access (CSMA). In CSMA, before every transmission of information the node that needs to transmit senses the channel to check if it is already taken by another node or not. In case the channel is occupied, the node postpones its data packet transmission to avoid a collision. Otherwise, when the channel is not being used, the node is allowed to use it to send the data packet. They suffer from poor performance, the goodput of the network degrades as the traffic load increases and the reduced flexibility leads to overprovisioning, protocol overhead, and complexity.

Reservation-Based protocols are a bit more complex than the *Contention-Based* ones, as they need to know about the network topology and the time synchronization between the elements of the network. So, as the name suggests, this type of protocols reserve slots to each node of the network, on which they can transmit information without interference or collision among transmissions. Thus, this approach will lead to a reduction of the collisions, considering that two nodes never transmit information over the air at the same time, and the fairness of the network increases comparatively to *Contention-Based* protocols, as each node, during its slot, is always able to transmit. Time Division Multiple Access (TDMA) is a scheme of the *Reservation-Based* protocols where time is divided into frames and each frame is divided into slots that are assigned to each one of the nodes, individually. Therefore, there will be no collisions, allowing a better goodput and fairer performance in the network as each node has opportunity to transmit through the channel, avoiding *starvation* situations. Even so, due to the slotting of the time, the throughput cannot be increased beyond the utilization of all the slots, which brings a limitation to this scheme. Despite all of the presented advantages of TDMA, there are some constraints as it needs to know the network topology and synchronize the nodes, unlike in *Contention-Based* protocols.

2.3.2 Wireless Sensor Networks MAC Protocols

Since WSNs [24] usually require low power devices and the radio is often the component of a sensor node that consumes most of its energy, its usage must be well coordinated in order to achieve robust and energetically efficient networks, exactly what it is sought to achieve in

LoRa networks. To do so, were developed and proposed several WSN-specific MAC protocols that aim these requirements and have different trade-offs between performance and power consumption. These can be divided into three main classes that are based on how the nodes are organized to gain access to the shared medium:

- **Random Access**: This is the simplest one; the nodes compete with each other to gain access to the channel. In order to reduce the time spent listening to the channel, the nodes shift the costs from the nodes to the sender by extending the MAC header, the so-called Preamble, allowing nodes to check the channel periodically and sleep most of the time, decreasing their power consumption. It allows the network to be extended, accommodating easily dynamic changes, without time synchronization nor previous knowledge about the network. The major drawbacks of this random access approach are the amount of power consumed both during the idle listening and when collision occurs.
- **Slotted Access**: This class is relatable to the *Contention-Based* protocols, mentioned before, where time is divided into slots and the network nodes transmit their packets at the beginning of each slot, agreeing on a common sleep/active arrangement. The probability of collision is higher than in *Random Access*, as all nodes access in the same active part of a slot. Thus, some slotted protocols include collision avoidance signalling, such as RTS/CTS handshaking, despite the large protocol overhead.
- **Frame-based Access**: The most complex of the three, the *Frame-based* protocol groups the slots into frames and assigns the nodes to each slot with detail. So, there are no data packet collisions in this approach and the time spent listening to the channel is considerably reduced. To achieve this, the nodes only listen to when they have the intent to receive any information from another network element, so the assigning of the slots must be accurate enough to the coordination between the sender and receiver of the information to occur at the exact same time. When only the senders are scheduled, the receivers must be always listening to the channel when the slots are occupied so to be able to receive the information. It can still avoid most of the overhearing because it can turn off the radio, the component that consumes most of the power in a node, after the receiving of the MAC header.

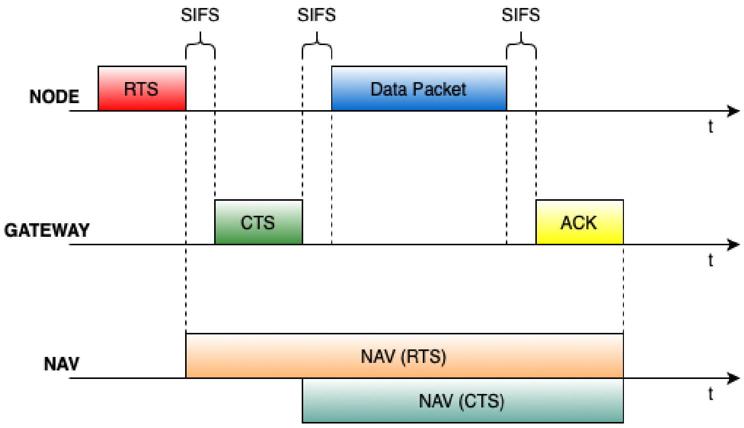
Thus, according to the needs of the applications of the WSN, there are three main classes of MAC protocols that are distinguished from each other mainly by their complexity, being that, the higher it gets, the better the performance of the network, namely regarding to the goodput of the network as the management of the accesses is done in a proper way and so, the number of data packet collisions is more reduced than with a simpler protocol.

2.3.3 RTS/CTS and NAV mechanisms

The Request To Send / Clear To Send (RTS/CTS) [29, 20], or virtual carrier sensing, mechanism is an optional feature of the IEEE 802.11 standard designed to control the access to the medium when collisions may occur due to the hidden node problem. When a certain node is using it, only sends a data packet when completed the RTS/CTS handshake with the gateway that will receive it.

Network Allocation Vector (NAV) is a carrier sensing mechanism implemented in wireless network protocols, such as IEEE 802.11, that plays a very important role in CSMA/CA. It is a counter found in the nodes that begins with the transmission time that a frame needs to be sent and decrements it down to zero. Thus, while this counter is not zero the channel is busy, preventing anyone else from accessing it. When the value reaches zero that means that the channel is free again and the other nodes can compete to access it.

In Figure 2.3 is shown the behavior of RTS/CTS and NAV mechanisms, using Short Interference Space (SIFS). So, the node starts by sending an RTS packet and NAV (RTS) is initialized, so that other nodes do not access the channel simultaneously, causing interference. When the gateway receives it, responds with a CTS packet, which initializes a NAV (CTS), that gives the node permission to send and contains the time that the other nodes must back off from accessing the medium. As the gateway receives the data packet, sends an ACK packet and, at the same time, both NAV values reach zero.



NAV (RTS) = 3 x SIFS + CTS + Data Packet + ACK

NAV (CTS) = 3 x SIFS + Data Packet + ACK

Figure 2.3: RTS/CTS and NAV scheme.

2.4 Related Work

A typical LoRa network is constituted by a huge quantity of EDs that transmit data packets to, at least, one GW, to which they send packets. Afterwards, the GW relays the information to a common Network Server. In a multi-GW network, it is important to take care of some aspects, as the coverage of the network, so that there are no areas without coverage, and also the management not only about the quantity of EDs that are associated with the several GWs of the network, but also the quantity of EDs that are using a certain channel.

The GW placement problems in LoRa networks are different from the GW placement problems in conventional wireless networks due to its association-less nature, *i.e.* every ED broadcasts its messages to the GWs with a single-hop, being no notion of GW-ED association [32], as the EDs simply transmit their data packet and any GW of the network can receive it. In contrast with LoRa, in WiFi networks, for example, a GW only receives messages from a device that is associated with it.

So, in order to be aware about the contributions on this subject, the remaining chapter discusses previous works that have addressed the performance of LoRa networks with multiple GWs and with a single GW, as much of the work done so far is referred to the later.

2.4.1 Single Gateway

With the aim to outperform the widely accepted basic ADR strategy, analysed by Hauser *et al.* [17], Cuomo *et al.* [11] proposed two algorithms. The first one, and the less complex, named EXPLoRa-SF, that, unlike the ADR strategy, in addition to using the distance and RSSI values, also uses the density of the network, *i.e.* the number of EDs that are in it, to assign the SFs. Next, Cuomo proposed and tested EXPLoRa-AT, a more complex algorithm based on the first one, that aims to allocate the SFs to the EDs in order to improve the throughput and the DER of the network. To do so, the method developed looks for providing a balanced distribution of the channel load among the EDs through the equalization of the ToA and hence, the increase of the fairness in the network. To simulate the behavior of the developed algorithm, they performed comparative tests with the standard ADR and EXPLoRa-SF, based on throughput and DER. The outcome of the performance tests shown that EXPLoRa-AT outperforms both ADR and EXPLoRa-SF not only on throughput but also on DER.

Cuomo *et al.* [12] considers a single GW scenario and derives both a model and an on-line resource allocation algorithm for managing the access to wireless resources. This, as the previous article under discussion [10], is based on the results of EXPLoRa-AT [11] strategy. In this work, the distribution of EDs follows a Spatial Point Process whose parameters are chosen so as to best approximate the random distribution of EXPLoRa-AT. In addition, it was also implemented a retransmission mechanism and a novel evaluation metric called REtransmission Data Extraction Rate (REDER), to evaluate the overall performance of the network. Finally, Cuomo also proposed and implemented in this work an SF allocation technique, called Real-Time SF Upgrade (RTSFU). This technique is able to be dynamically executed on-line, while the network is running. Thus, the EXPLoRa-AT allocates the SF offline and then, at run time, the SFs are adjusted given the collisions measured by the nodes. Note that the complexity of EXPLoRa-AT is kept at the Network Server during the initial SF allocation.

Ousat *et al.* [32] developed an algorithm for planning large-scale LoRa networks efficiently, with focus on the GW placement and device configuration. The best way to perform GW placement, according to the authors, consists of finding the optimal locations to install them and deciding on the SFs and transmission powers of each ED of the network. Therefore, were developed two strategies for optimal EDs spreading factor allocation. The first one, called *EquiP* strategy, is based on the distance between the ED and its target GW, *i.e.* lower SFs are assigned to EDs nearest to its GW and higher SFs are assigned to EDs further away from the GW. This strategy, despite being optimal in terms of Packet Delivery Ratio (PDR) does not respect the constraints in terms of transmission power. In order to suppress this, it was developed a new strategy, called *Hybrid* strategy, that uses the optimal SF allocation, given by the *EquiP* strategy, followed by the assignment of the lowest possible value of SF to the EDs that violate the power constraints. In the following, Ousat *et al.* performed simulation to evaluate the strategies developed, comparatively to the basic ADR. The obtained results show that the *Hybrid* strategy outperforms ADR in all iterations, while maintaining the power violation low, and its level of performance as high as the *EquiP* strategy that, in contrast, presents a power violation of, at least, 30%, meaning that this percentage of EDs violated the power constraints.

Due to the lack of efficiency of ADR in a large class of IoT applications, Benkhla *et al.* [7] developed a mechanism to enhance the ADR mechanism, as Cuomo *et al.* [11] did, by taking into account the position and trajectory of the EDs in order to have a dynamic allocation. To do so, the mechanism reconfigures the channel of the EDs based on the estimation of the next position and predefined trajectory. The allocation model is driven by the network server and, contrary to the basic ADR, the server can either increase or decrease the configuration channel. As soon as the new position is defined, the server calculates the corresponding RSSI and searches for the best RSSI interval in which it can be located to determine the most suitable channel. As the simulations can show, the Enhanced-ADR, name given to the developed mechanism, improves the quality of service of the overall networks. It solves the issues of ADR such as low adaptation speed and low performance, as well as the power consumption and ToA.

Amichi *et al.* [3] presents an algorithm that enhances the minimal user rate, network throughput and fairness, compared to baseline SF allocation method such as *Random SF* and *Distance SF*. In the former, the GW chooses an random number of EDs and assigns to them a random SF value and, in the later, the GW chooses a random number of EDs and assigns to them SF values according to their distance. So, it is proposed a *many-to-one algorithm* between the set of possible SF values and the set of EDs. Thus, the scheduler,running in the GW, matches the two sets, firstly, according to distance and then, to ensure that there is a balanced number of EDs for each SF value. This swap is repeated until the algorithm considers that a two-sided stable matching is reached. The tests performed show that the proposed algorithm outperforms both the conventional random and distance allocations for any number of EDs located in the network regarding throughput and fairness to the network.

Reynders *et al.* [35] realized that in LoRa destructive collisions happen when nodes far from the GW try to transmit data at the same time as the closest ones. Furthermore, LoRa spread spectrum technology is very sensitive to this effect, called *near-far effect*. Thus, Reynders, in order to suppress the consequences of this effect, developed a scheme that not only optimizes the power and the spreading factor for each node but also avoids the *near-far effect* allocating different channels to nodes more distant from the GW. This optimizes the PER fairness inside a LoRaWAN cell, decreasing it up to 50% for edge nodes.

Abdelfadeel *et al.* [1] developed FADR, Fair Adaptive Data Rate algorithm, to select SFs and transmission power in order to achieve a fair data extraction rate among all EDs. This time, the allocation of SFs is based on the optimal SF distribution for fair collision probability using RSSI and power levels. This technique, simulated in LoRaSim, shows a fairness increase of 300% comparatively to the technique proposed by Bor *et al.* [8] and 22% more fairness than the scheme proposed by Reynders *et al.* [35] on which the allocation was based, as mentioned earlier. It should be noted that, when compared to the later, there was also a decrease of 22% in energy consumption.

Regarding to power allocation, Kumari *et al.* [23] proposed a game theory model in order to eliminate the greedy behaviour of the LoRa EDs relatively to the power allocation. To do so, it was proposed a Stackelberg Game based model for an efficient allocation of power levels to the LoRa EDs. In this, network server and EDs work as a leader and followers assigning power levels to the EDs and estimating the respective price and duration, in order to reduce the power consumption of the EDs and thus, transmit the data in the given time.

2.4.2 Multiple Gateway

Cuomo *et al.* [10] uses the idea of EXPLoRa-AT [11], based on balancing the ToA of the EDs, and extended it to a multi-GW scenario. In this type of scenario there are certain aspects that must be taken into account that do not occur when the scenario is single GW. Such situation can be a data packet, sent by an ED, being received by multiple GWs, which are using the same channel as the ED. So, as to ensure that there is no overuse of a certain channel, which would cause a large number of collisions, Cuomo *et al.* proposes an ADaptative Mitigation of the AIr-time pressure in lORA (AD MAIORA). This method allocates the SFs, not only distributing the load of the network by the different channels but also by the different GWs. Hence, the balance of the number of EDs per GW and the visibility of different EDs to the GWs are the aim of AD MAIORA. Performance tests have shown that AD MAIORA presents a considerable improvement over the basic ADR approach and it should be also noted that in highly stressed scenarios, *i.e.* when EDs transmit with a message period equal to 10 seconds, as well as in unbalanced ones, the improvements are even more evident.

Zou *et al.* [39] proposed *hybrid LoRa networks* in order to achieve higher capacity and sensitivity, better flexibility and scalability. The authors state that GW planning is a critical piece in *hybrid LoRa networks* because when EDs are, for example, co-frequency nodes, they need more than one type of GW to provide service to them due to the frequency mismatch between their uplink and downlink frequency bands. So, Zou enhanced the Reliability Of Connections (ROC) by increasing the number of GWs that serve a certain node. Also, they have developed a heuristic algorithm named *Dynamic Weighted Greedy Algorithm* (DWGA). In this, dynamic weights are assigned to EDs to guarantee a trade-off between local optima and global optima. DWGA starts to select one GW in each round and, for each ED, it is assigned a dynamic weight according to the *urgency* of providing a service. This way, the algorithm makes a decision of what GW is able to communicate with most EDs. In fact, its performance turned out to be better than the *Original Greedy Algorithm* (OGA), achieving the same level of time complexity as it. Furthermore, in small-scale networks, DWGA achieved an approximate solution of 95% to the optimal ones.

Liao *et al.* [26] explored the characteristics of a multi-GW LoRa network and proposed a novel method able to, in a dynamic way, make the selection of the serving GW and also, allocate the most appropriate channel, considering the PER for each ED of the network. So, as every ED needs to know its PER, the method uses ACK/NAK signaling after every up-link transmission. So, the proposed method re-selects the serving GW of an ED when there is another GW with better transmission conditions and re-allocates a new SF value to the ED when the number of recent NAK signals surpass a certain threshold. To proceed to the GW re-selection, the method is based on the RSSI value between each GW and ED pair, whilst to do the SF re-allocation, in order to minimize the probability of data packet collisions, first the EDs are distributed by the several SF values, ensuring that there are not any SF with a greater number of EDs than the others, and then the allocation itself is done according to the accumulated PER and RSSI values of each ED. Performance tests regarding the BER and PER showed an improvement of 35% and 29%, respectively, when compared to the traditional SF allocation, based only on the RSSI values. Also, the PCR decreased as well.

As ADR does not exploit all the LoRa technology potential, presenting some limitation, namely the SF allocation based exclusively in the RSSI values that can lead to *over-usage* of a given channel and *under-usage* of another, Ochoa *et al.* [30] proposed the Enhanced Link Adaptation (ELA) method. This method binds the EDs to the GW, finding its optimal SF configuration, in order to improve the network performance. In case the chosen SF for a given ED already reached its maximum capacity, *i.e.* the maximum number of EDs using it, the method checks which one of the other available SF options is not overloaded and uses it. However, if all SFs are overloaded, the GW maintains the number of EDs in a certain SF proportional to the percentage of EDs supported by each SF. If this is not possible, it chooses instead the optimal configuration according to the network link budget. When compared with basic ADR and a network where all ED are bound to the same SF, the ELA method decreases collisions and improves the PDR, ensuring a better overall network performance with a cleverer usage of the available SF options. Furthermore, the ELA method with multiple GW in the network concluded that increasing the number of GWs the coverage of the network will be bigger and the PDR improves.

Table 2.1 presents a summary of each one of the works discussed in this chapter, referring the used scheme and the improvements provided, with respect to a certain work that served as a starting point to the development of the new method.

So, the related work presented in this section proposes methods that were developed with the aim of improving the performance of a LoRa networks, regarding their capacity, fairness and even the energy consumption of its elements. In general, the multi-gateway methods are based on assigning the correct channels for each ED in a balanced way, not only regarding to the number of EDs using each SF value but also the number of EDs using each GW, so that there is less risk of collisions. In our work, apart from the assignment of channels to the EDs, that is based on the RSSI value, we introduced control packets, to manage the access to the medium, and the GWs, using a single channel, can change their communication parameters during their execution, so to allow the transmissions to be more efficient.

2.5 Final Remarks

The present chapter introduced the LPWANs and their main characteristics that allowed them to emerge in the market of the IoT, and also, the different LPWAN technologies, both for unlicensed and licensed bands of the spectrum. Since this work is mainly focused on the use of LoRa technology, it has received more attention with the introduction of its main features, network architecture and communication protocol defined by the LoRaWAN standard.

In the following, the traditional MAC families were presented and, as long as this work is focused in large-scale LoRa networks, WSN MAC protocols were presented as well as they share some common concerns.

In the end of the chapter, the most recent related work relevant to this dissertation was presented and discussed. It focused on works that propose device configuration schemes and performance studies, for single and multiple gateway networks, with similarities to the work done in this dissertation.

Table 2.1: Summary of the works overviewed in the Related Work Section.

	Method Scheme	**Improvements**	**Comparison Basis**	**GW Scheme**
EXPLoRa-SF [17]	- SF allocation based on the distance , RSSI and on the density of EDs in the network.	- Allocation of more adequate SFs for each ED.	ADR [17]	Single Gateway
EXPLoRa-AT [17]	- Not only do what EXPLoRa-SF does but also balance the distribution of the channel load by the different SFs.	- Equalization of the ToA in the network.	EXPLoRa-SF [17]	Single Gateway
RTSFU [12]	- Uses EXPLoRa-AT to make offline SF allocation and, during run time, uses the function of the packet collision measured by the EDs to adjust it.	- Adjust the SFs in a dynamic way.	EXPLoRa-AT [17]	Single Gateway
EquiP [32]	- Allocation of SFs using distance between the EDs and the GW.	- Optimal in terms of PDR.	ADR [17]	Single Gateway
Hybrid [32]	- SF allocation based on the distance between the EDs and the GW, as the EquiP method; - Assign the lowest possible value of SF to the Eds that violate the power constraints.	- Avoid the violation of the power constraints that were recurrent in the EquiP method, maintaining the high level of performance.	ADR [17] and EquiP [32]	Single Gateway
Enhanced-ADR [7]	- SF allocation based on the position and trajectory of the EDs.	- Dynamic SF allocation, adjusting its value when needed.	ADR [17]	Single Gateway
Many-to-one algorithm [3]	- First allocates according to the distance between the EDs and the GW and then, according to the number of EDs that are already using each SF, to avoid overuse.	- Avoid the overuse of some SFs and the underuse of others, distributing the EDs for the available SFs.	Random SF and Distance SF	Single Gateway
Scheme [35]	- Allocates different SFs to EDs that are located further from the GW and so, with poorer transmission conditions.	- Suppress *near-far effect* present in basic allocation methods.	ADR [17]	Single Gateway
FADR [1]	- Optimal SF distribution using RSSI and power levels.	- Fair collision probabilities.	[35] and [8]	Single Gateway
Game theory algorithm [23]	- Assigning the most reduced power level possible to the EDs, accordingly to their needs.	- Eliminate the greedy behavior of the EDs relatively to power allocation.	ADR [17]	Single Gateway
AD MAIORA [10]	- Extends the EXPLoRa-AT to networks with multiple GWs, balancing the distribution of the channel load not only by the different SFs but also by the different Gateways.	- Presents a good performance for highly stressed network scenarios.	EXPLoRa-AT [11]	Multi-Gateway
Hybrid LoRa Networks [39]	- Uses DWGA, developed in the same work, to assign dynamic weights to the EDs.	- Higher capacity and sensitivity, better flexibility and scalability. - The allocation method guarantees a good tradeoff between local optima and global optima.	Original Greedy Algorithm (OGA)	Multi-Gateway
Novel Method [26]	- SF allocation based on the PER of every ED, balancing the EDs to each SF; - The GW allocation is based on the RSSI between the ED and the GW.	- Reduce the PER, BER and PCR of the transmissions.	Traditional SF Allocation	Multi-Gateway
ELA [30]	- Finds the optimal SF configuration, in a balanced way. - The GW maintains the number of Eds in a SF proportional to the percentage of SFs supported by each SF.	- Improve the network performance, increasing the PDR.	ADR [17]	Multi-Gateway

Chapter 3

Static Channel Protocols

This chapter is about the medium access in LoRa networks with multiple gateways and single-channel transceivers. Two MAC protocols are under study, a pure-ALOHA protocol, used in LoRaWAN networks, and a protocol based in control packets. The later ensures that every data transmission is announced, reducing the number of collisions in the medium, relatively to the pure-ALOHA protocol. Section 3.1 overviews the pure-ALOHA protocol, its operation principles, and the behavior of the EDs. Section 3.2 details the control-based protocol and its two side versions. Section 3.3 evaluates the performance of both protocols in a multiple gateway scenario. The evaluation platform, the network characteristics and the performance metrics are introduced before the results. Section 3.4 concludes the chapter.

3.1 Pure-ALOHA based Protocol

As a starting point, a pure-ALOHA protocol was used, as it is also used in LoRaWAN networks, so as to serve as a basis of comparison with the other protocols tested in this dissertation. This protocol stands out for having reduced to none complexity, as each ED transmits a packet whenever it wants to, without sensing the channel to check for ongoing transmissions.

Although being known that in a pure-ALOHA based protocol the EDs can send data packets as soon as they want to, because we are considering a LoRa network, there is an obligation for each element of the network to respect the duty-cycle restriction, inherent to every data transmission, being it an ED or a GW. Thus, after every data packet transmission, the transmitting element must wait for, at least, ninety-nine times the ToA of the data packet that was sent. The behavior of the EDs is presented in Figure 3.1.

In order to decrease the probability of successive data packet collisions, caused by two EDs using the channel at the same time, the protocol adds a random time window. Thus, in this protocol, the backoff time calculated after every data packet transmission is given by

$$\text{Backoff} = \text{Mandatory\_Backoff} + randi([0,\ n]),$$

where n represents the maximum time window value, *randi* returns a random integer number and *Mandatory_Backoff* is the mandatory backoff time that the ED must wait after every transmission. If such additional time is not summed to every mandatory backoff time after a transmission, two transmissions with the same packet length colliding in a first instance, would collide in every subsequent transmission. This would result in a major loss of information.

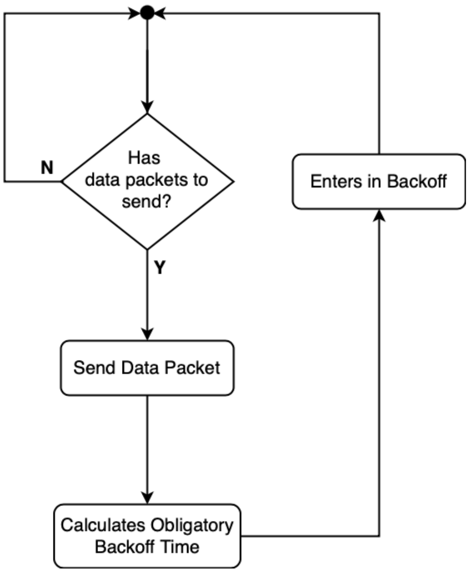


Figure 3.1: ED behavior with pure-ALOHA Protocol.

During this restriction time, the ED stays in the Backoff state without accessing the channel. As soon it comes to an end, the ED goes to the Idle state and can send a data packet again.

In case of a data packet collision, as we are in the presence of a LoRa network, if the difference of RSSI values between the two colliding data packets is above a certain threshold, the one with the higher value has a better chance to be decoded by the GW according to the study [29]. Due to the lack of access control, it is expected to have a high number of collisions, a number that will increase with the number of EDs in the network.

3.2 RTS protocol

The absence of control packets in the pure-ALOHA scheme is reflected in the number of data packet collisions, goodput and fairness of the network, as the network scales. Thus, control packets were introduced, Ready-To-Send (RTS) packets, to manage the channel access, in order to reduce the number of collisions.

3.2.1 Protocol Overview

Every time an ED decides to transmit, first it listens to the channel and then, three situations may occur:

- The ED overhears an RTS packet, sent by one of its neighbor EDs, and its transmission is postponed. At the same time, the ED recovers from the overheard control packet the information about the size of the advertised data packet transmission and calculates the ToA, entering in a backoff state in order to avoid interfere with it;

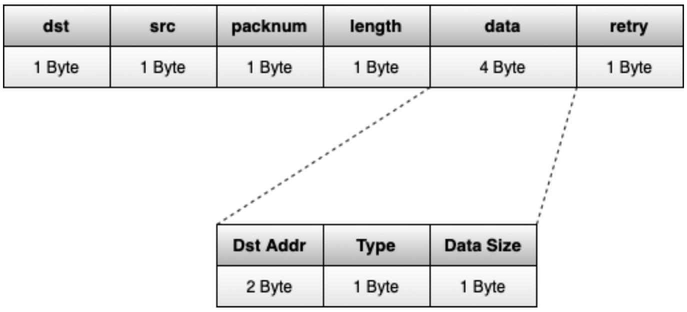
- The ED does not overhear any RTS packet and therefore, it sends its own RTS packet. As soon as the control packet transmission ends, the ED proceeds to the transmission of the data packet to the GWs in its reach of communication. Then, it calculates the mandatory time for the backoff to respect the LoRa restrictions of duty-cycle along with a random value of backoff slots, that have the duration of an RTS packet ToA. After that, it goes to the Backoff state and waits there for its next transmission opportunity;

- If two RTS packets collide, the same thing as when two data packets collide happens, the one with the better RSSI value is more likely to be received successfully, thanks to the non-destructive property of LoRa. Thus, RTS packets are not always successfully received by neighbor EDs, being the worst case when none of the colliding packets reach the EDs, which consider that the channel is free, transmitting their packets as well.

So, RTS packets are sent by EDs willing to access the channel, and therefore reducing data packet collisions. The EDs receiving an RTS use the advertised data packet size, which it is contained in the control packet, to calculate the minimum time that they must back off, so they do not interfere with the advertised transmission. The hidden terminal problem is not solved in this protocol, as the RTS packets are received, at best, by the neighboring EDs of the one that transmits it. Therefore, two EDs could be able to transmit packets to the same GW, at the same time, and, as they do not overhear RTS packets from each other, their data packets will collide at the receiver.

RTS Packet Structure

The packet structure used for the RTS packets is similar to the one used by Rui Fernandes *et al.* [29], based on the one defined by the SX1272 LoRa module support library. So, the one used is shown in Figure 3.2, with the following structure:



dst	src	packnum	length	data	retry
1 Byte	1 Byte	1 Byte	1 Byte	4 Byte	1 Byte

Dst Addr	Type	Data Size
2 Byte	1 Byte	1 Byte

Figure 3.2: RTS packet structure.

- **dst** - Address of the destination node;
- **src** - Address of the node that sent the packet;
- **packnum** - The packet number. It has the length of 1 byte and so, starts in 0 and restarts the counting as soon as it reaches to 255. If the packet is trying to be retransmitted, the packet number is not incremented;
- **length** - The total packet length;
- **data** - It is where all the data that it is intended to send is stored and its total length is variable with a maximum of MAX PAYLOAD, a constant defined in the SX1272 module library;

- **retry** - It is usually equal to 0. Only when we use the retries feature, this value is incremented from 0 to the maximum number of retries, value which is configurable. If the packet is sent successfully, or if the maximum number of retries is reached without success, the retry counter is set to 0.

Within the data field, there are 3 subfields that contain the information that EDs overhearing the RTS packet will use to get ready for the advertised transmission. Such subfields, also represented in Figure 3.2, are the following:

- **Dst Addr** - Address of the GWs that might receive the advertised data packet. This information is known by the ED that is sending the packet by knowing its own position and the position of the network GWs. This information is used by protocols, which will be presented further ahead in this dissertation, where each ED filters the RTS packets according to the advertised packet destination. This parameter does not define to which GWs the packet is being sent to, every data packet is sent in broadcast, only advertise the GWs which could decode the data packet at the moment;

- **Type** - Identifies if the present packet is a control packet or a data packet;

- **Data Size** - This field indicates the size of the advertised data packet, so that the EDs that receive it are able to know the minimum backoff time that they must take, in order not to interfere with the transmission.

3.2.2 Protocol Description

As in the pure-ALOHA protocol, in the RTS protocol each ED begins in the Idle state, using the same configuration parameters as the GWs, ready to send a data packet as soon it sees an opportunity. To do so, according to Figure 3.3, first it listens to the medium, seeking for any control packets from any of its neighboring EDs.

If, for instance, it overhears a control packet, the ED postpones the transmission and takes the steps to back off, avoiding a collision that would be imminent. So, the ED uses the advertised data packet size, in the received RTS packet, to calculate its ToA. Therefore, as soon as it knows exactly how much time the current transmission will take, as mentioned before, a random number of RTS packet slots will be added to the backoff period.

At this moment, the ED knows the exact time it has to wait, jumping to the Backoff state, whose operation mode is shown in Figure 3.4. During its stay in this state, in a first instance, it goes into sleep mode and, as soon as the remaining time is lower than the time needed to send a data packet, it starts to listen to the channel. In case it overhears an RTS packet, the ED double checks if the remaining backoff time is lower than the time that the advertised packet will take to be sent. In such case, the ED updates its backoff time. Otherwise, it keeps the actual backoff time.

As soon as the ED ends the backoff period, it returns to the Idle state, where it will try to send a data packet. If it does not overhear any RTS packet from other EDs, the ED starts competing for the channel. First, the ED sends an RTS packet. Despite the use of these control packets, collisions may occur, although in a smaller scale compared with pure-ALOHA protocol, where there is no control in the access to the medium. To take care of them, the same probabilistic collision model used on the previous protocol is also used, since it is a LoRa network.

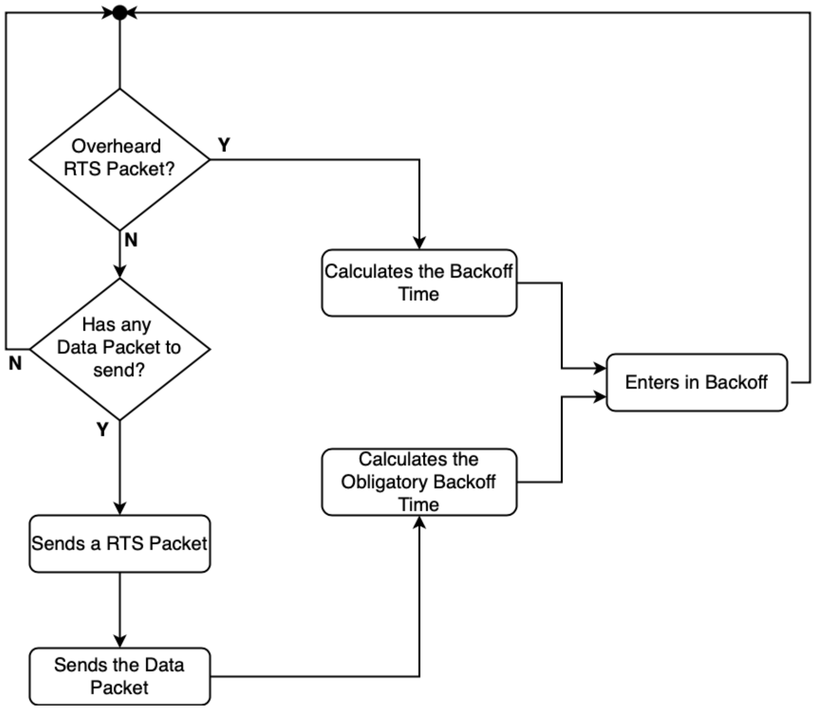


Figure 3.3: ED behavior in the Idle state using RTS protocol.

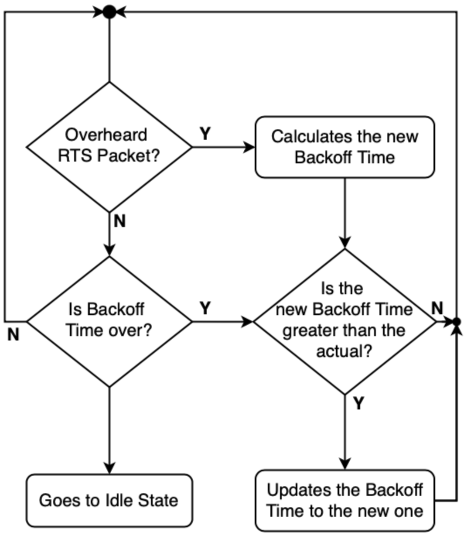


Figure 3.4: ED behavior in the Backoff state using RTS protocol.

As there are no Acknowledgment (ACK) packets in such protocol, the ED does not have any way to know if the data packet was successfully delivered, and considers that every transmission was successful.

After the RTS packet transmission, the ED sends the data packet and proceeds to the calculation of the backoff time in order to comply with the mandatory duty-cycle restriction of the unlicensed band of frequencies used by the LoRa networks. To do that, it must consider the ToA of both RTS and data packets. Additionally, the protocol adds a random number of slots multiplied by the ToA of an RTS packet. Thus, in this protocol, the backoff time calculated after every data packet transmission is given by

$$\text{Backoff} = \text{Mandatory\_Backoff} + (randi([0,\ n]) * ToA(\text{RTS\_Size})),$$

where n represents the maximum number of backoff slots, *randi* returns a random integer and RTS_Size the length of a RTS packet.

As soon as the backoff time comes to an end, the ED goes back to the Idle state so it can prepare a new data packet transmission.

3.2.3 Versions of the RTS protocol

Two versions of the RTS protocol were used in this dissertation. The difference lies on the method used by the EDs to filter received RTS packets. Whereas in the first version every RTS packet overheard by an ED is considered by it, in the second version the EDs discard any received RTS packets targeting GWs that are not in their reach of communication. Such information is contained in the received RTS packet, being used by the EDs to make the decision. We expect improvements in the network performance because some EDs will not back off unnecessarily, thus making a better use of the medium.

Therefore, the two versions are presented below:

- **RTS v1**: The RTS v1 follows the rationale explained in section 3.2.2 and is characterized by having a maximum of 50 backoff slots, no matter the size of the network. The behavior of the EDs and GWs using this protocol version are shown in the Figures 3.3 and 3.4, respectively.

- **RTS v2**: In the RTS v2, the EDs have the capability to decide if the received RTS packets are worth to be considered or not, knowing its own position, the position of each static GW and the maximum reach of a packet transmission. The decision is based on the destination of the data packet, advertised by RTS packets. If targeting a GW on the communication range of the ED, it should be considered. Otherwise, it is discarded. This behavior is shown in the Figures 3.5 and 3.6 represented by a grey box. The rationale behind this is that two data packets can be sent simultaneously if each one of them can only reach different GWs from the other. To better explain the rationale, let us consider Figure 3.7, where the green and black crosses represent gateways GW1 and GW2, respectively, the blue circles are EDs of the LoRa network and the red circumferences the maximum coverage range of both GWs. If the green ED (A) overhears an RTS packet sent from the yellow ED (C), it can discard it, when using RTS v2, as the advertised packet can only be received by GW2, which is out of its reach. Therefore, even if both the green and yellow EDs send a packet simultaneously, as they can only reach different GWs, there will be no interference. On the contrary, if the orange ED (B) receives a control packet of the green or yellow ED, it must back off as it is in reach of both GWs.

  This feature will allow the EDs located close to the network overlap to access the channel more often than before.

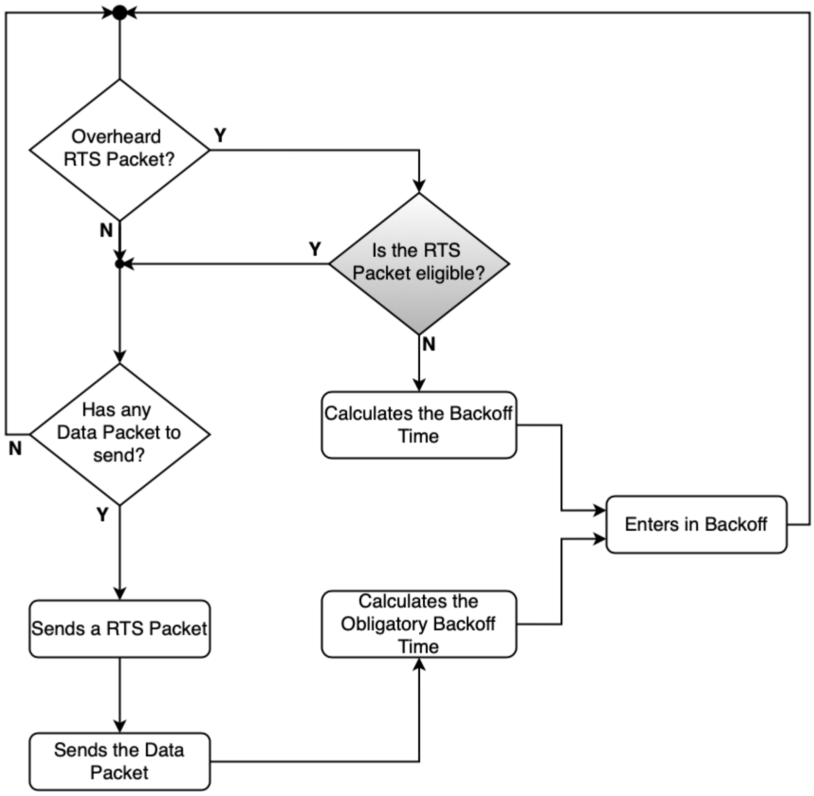


Figure 3.5: ED behavior in the Idle state using RTS v2.

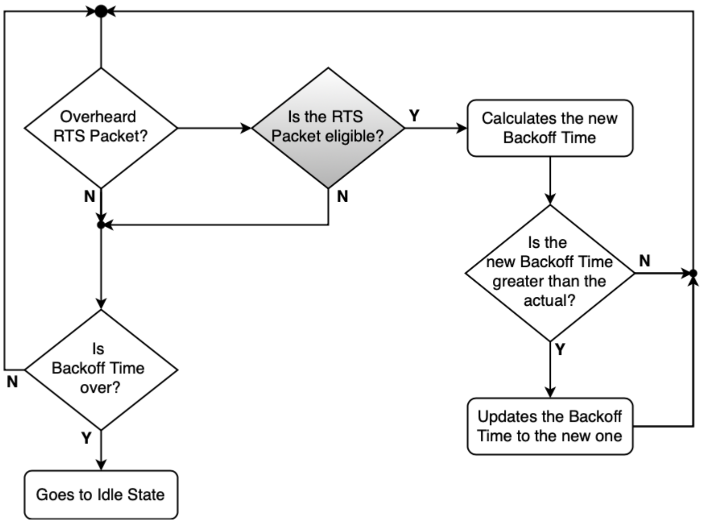


Figure 3.6: ED behavior in the Backoff state using RTS v2.

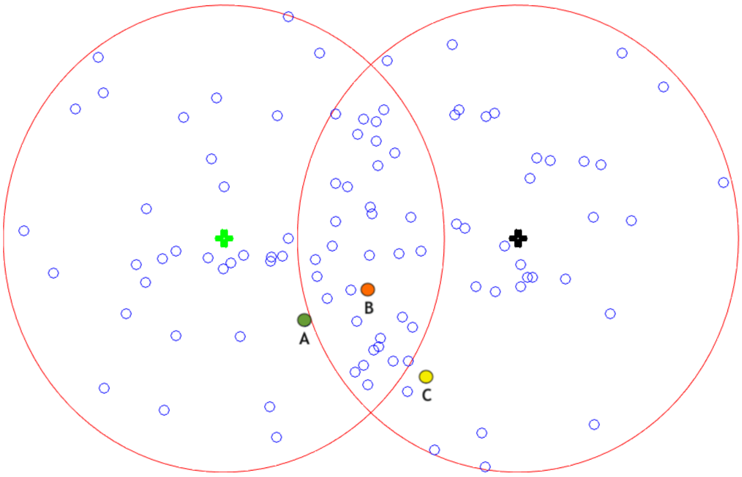


Figure 3.7: LoRa network with 100 EDs.

3.3 Protocol Comparison

Presented the two protocols, and respective versions, it is now time for a preliminary evaluation. First, it is presented the simulation environment, followed by the comparison between both versions of the RTS protocol. At last, a performance analysis is made regarding the goodput and fairness of the network with the pure-ALOHA and RTS protocols, in order to conclude about the introduction of packets to manage the access to the medium by the EDs.

3.3.1 Simulation Environment

Large-scale networks are very difficult to test in real life deployments. So, it is important to have tools capable of representing the behavior of the network. Thus, a MATLAB simulator was developed for each one of the protocols, from which the results presented in this dissertation were obtained.

The simulation time was chosen in order to guarantee that every ED has the opportunity to send packets, no matter how crowded is the network. So, the chosen value was 3×10^8 ms, that correspond to, approximately 83.33 hours, about three and a half days. During that time, the EDs are able to send data packets, as long as they are allowed to do it. The data packets are generated periodically, so that every ED has always a packet ready to transmit, avoiding the scenario where the EDs are not restricted and yet are unable to send, affecting the performance of the network. Relatively to the length of the packets, the data packets have always 100 bytes and the RTS packets 9 bytes.

For each performance test, the number of EDs in the network varies between 100 and 950 and the number of GWs was fixed to two, horizontally apart to form a network with the same appearance as the one displayed in Figure 3.8. In the figure, the green and black crosses represent gateways GW1 and GW2, respectively, and the blue circles are the EDs that populate the network. The circumferences centered in each one of the GWs represent the maximum distance the EDs can be in order to be able to communicate with each GW, being the coverage of the network limited by them. As shown in Figure 3.8, the coverage of each GW has an overlap zone, where the EDs are able to communicate with both of them.

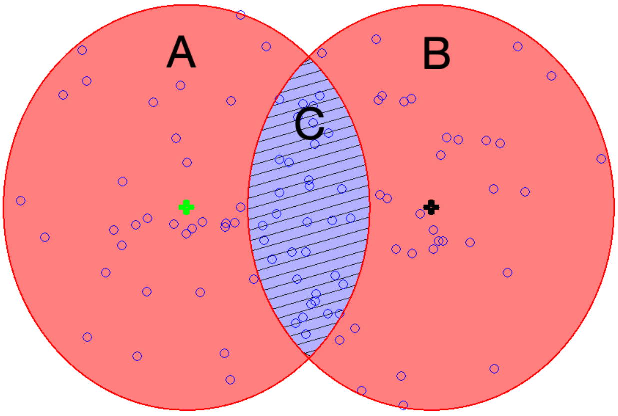


Figure 3.8: Network map with 100 EDs and two gateways, GW1 and GW2 shown as a green and black cross, respectively. 'A' and 'B' represent the network zones only reachable by GW1 and GW2, respectively. 'C' is the overlap zone of GW1 with GW2.

It was generated a map of EDs that was used throughout the tests, so that the tests of the different protocols were not influenced by the location of the EDs in the network. They were distributed by the different zones of the network in the following way:

- **GW 1 (A)**: 1/3 of the total number of EDs;
- **Overlap Zone (C)**: 1/3 of the total number of EDs;
- **GW 2 (B)**: 1/3 of the total number of EDs.

Therefore, each GW has only in its exclusive reach 33% of all EDs and the remaining 33% are in the overlap zone, reachable by both GWs. Depending on each density case, the overlap zone gets more or less one ED, in case the division of the EDs by the zones does not return an integer. Table 3.1 shows how many EDs are placed in each zone according to the total number of EDs in the network that were tested.

To simulate the non-destructive property of LoRa, when a collision between two data packets occurs, was used a probabilistic model derived by Rui Fernandes *et al.* [29] that

Table 3.1: Number of EDs per zone of the network.

# EDs	**Each GW**	**Overlap**
100	33	34
150	50	50
175	58	59
200	67	66
250	83	84
300	100	100
400	133	134
500	167	166
600	200	200
700	233	234
750	250	250
850	283	284
950	317	316

determines which one of them will be received by the GW, based on the RSSI of each transmission at the receiving GW. The higher the gap between the RSSI of both data packets, the higher the probability to the one data packet with better value to be decoded successfully by the GW. When there are multiple interferers, the likelihood of a successful packet decoding at the GW decreases.

3.3.2 Evaluation Metrics

To evaluate the performance of each one of the protocols under study, evaluation metrics were chosen. So, to evaluate the quantity of information that it is delivered correctly by the EDs to the GWs, goodput was selected. This metric evaluates the quantity of useful information, in bytes, correctly decoded by the network GWs, per hour. Thus, to calculate the goodput only data packets are considered.

To evaluate the quantity of collisions in the network, it is used a ratio between the number of packet collisions that happened in the network during its execution and the total number of times that the EDs accessed to the medium to send a data packet. Note that, thanks to the non-destructive property of LoRa, a collision does not mean that all packets involved are lost. So, even if this metric is equal to 100%, meaning that all transmissions collide, does not mean that all of them are incorrectly decoded by the GWs.

To evaluate the fairness was used Jain's Fairness Index [19], calculated by

$$\jmath(x_1, x_2, ..., x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \times \sum_{i=1}^{n} x_i^2},$$

where n is the total number of EDs in the network and x_i is the individual normalized goodput of the ith ED given by

$$x_i = \frac{T_i}{G_i},$$

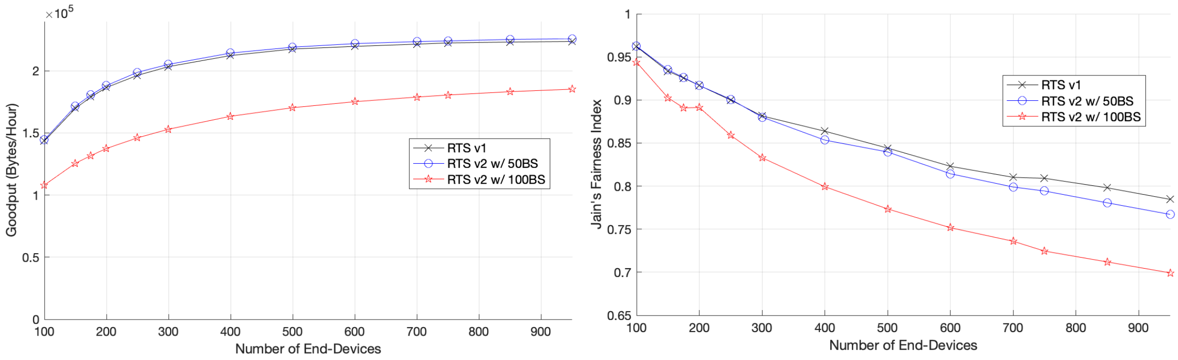
where T_i is the obtained goodput for the ith ED and G_i is the ideal goodput value for the ith ED, which is the number of generated packets.

3.3.3 RTS Versions Comparison

A performance comparison of the network when using the two presented versions of the RTS protocol will be now presented. Version 2, which has originally a maximum of 50 Backoff Slots (50 BS), was also tested with a maximum of 100 Backoff Slots (100 BS), resulting in a longer period of contention.

As shown in Figure 3.9a, the goodput of RTS v2 with 50 BS is the best, delivering a greater quantity of information (bytes per hour) than the other versions, despite the difference to the first version being very small. Regarding RTS v2 with 100 BS, it is the one with the worst goodput, mainly due to the higher ED contention time.

Regarding the fairness, as shown in Figure 3.9b, RTS v1 and RTS v2 with 50 BS present very close results, although, above 300 EDs RTS v1 performs better than RTS v2. On the other hand, RTS v2 with 100 BS is the one with the worst performance. This is due to the doubling of the contention period, from 50 to 100 backoff slots, which reduces the number of accesses to the channel by the EDs and so, the fairness decreases as well.



(a) (b)

Figure 3.9: Goodput (a) and fairness (b) of the RTS protocol.

Due to the performance similarity of RTS v1 and RTS v2 with 50 BS, it was decided to suppress the results of RTS v1 in the comparisons that follow in this dissertation. In fact, the goodput of RTS v2 with 50 BS is just 0.98% higher than RTS v1's for a LoRa network with a total of 950 EDs. The decision to maintain RTS v2 with 50 BS instead of RTS v1 was due to the better performance results, despite the small difference, that is provided by the increase in complexity of the protocol, where the EDs have the ability to discard RTS packets which do not affect them directly.

Regarding RTS v2 with 100 BS, as the values of the goodput and fairness differ considerably from the others, it is maintained in the following comparisons to study the effect of the contention window in the network performance.

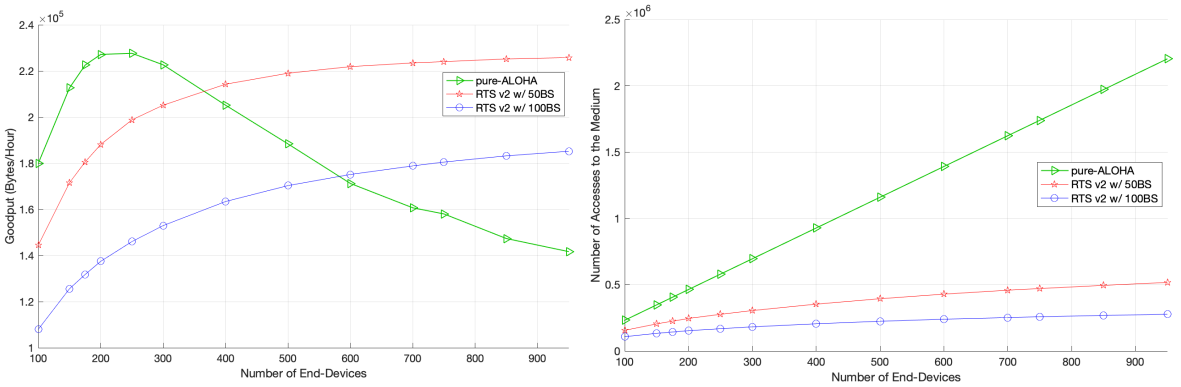
3.3.4 Pure-ALOHA Protocol vs. RTS Protocol

The evaluation of both protocols is now presented, regarding the goodput, number of channel accesses, percentage of collisions and fairness of the LoRa network, for different network sizes, with the pure-ALOHA and the RTS protocols.

3.3.4.1 Goodput Analysis

The pure-ALOHA protocol achieves the best performance of the tested protocols when the network has a small number of EDs, under, approximately, 366 EDs, as shown in Figure 3.10a. This is due to the freedom that the EDs have in this protocol, accessing the channel more times than when using the RTS protocol, as shown in Figure 3.10b, as the absence of control packets does not allow them to know if another ED is using the channel and thus, the duty-cycle restriction is the only restriction that they need to comply with.

As the network size increases, and while the goodput of RTS v2 improves, the pure-ALOHA gets worse, starting to decrease when the network surpasses the 250 EDs threshold and maintaining the decreasing behavior until the network has 950 EDs, the maximum number of EDs tested. This decrease in the goodput is due to the increase of the collisions in the network, as shown in Figure 3.11. In fact, the percentage of packets that collide when the goodput of pure-ALOHA protocol starts to decrease exceeds the 95% and, as the network size increases, this percentage tends to 100%, which means that every transmission results in



(a) (b)

Figure 3.10: Goodput (a) and number of channel accesses (b) of the RTS v2 and pure-ALOHA protocols.

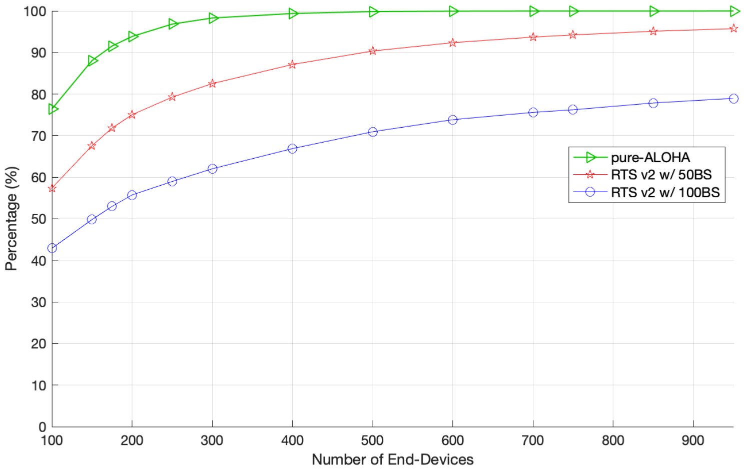


Figure 3.11: Probability of a packet collision when accessing to the channel of the RTS v2 and pure-ALOHA protocols for different network sizes.

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a collision and thus, the probabilistic model decides which colliding packet reaches the GW successfully based on RSSI values.

Distinct from the behavior of the pure-ALOHA, the goodput of both RTS v2 variations improves, as the network grows. The growth is sharp in the beginning and then, from 500 EDs onwards, it becomes less pronounced for both of them. For a small number of EDs in the network, the goodput is poorer than with pure-ALOHA protocol, as the reduction of collisions does not compensate the decrease in the number of channel accesses. However, as the network grows, the performance of pure-ALOHA protocol degrades and RTS v2 with 50 and 100 backoff slots outperform it for, approximately, 350 and 600 EDs, respectively. Therefore, it is from this network size that the usage of control packets starts to make the difference, as the decrease in the number of collisions pays off the lower number of channel accesses, comparatively to the pure-ALOHA protocol. RTS v2 with 100 BS surpasses the goodput of the pure-ALOHA protocol after RTS v2 with 50 BS, as the average contention time applied doubled.

Higher contention periods are reflected in the number of packet collisions, which is always lower than the others. Actually, for 950 EDs it is about 17% lower than for RTS v2 with 50 BS, which means that, for a higher number of EDs, RTS v2 with 100 BS could overcome the goodput of RTS v2 with 50 BS.

3.3.4.2 Fairness Analysis

Regarding the network fairness, as shown in Figure 3.12, pure-ALOHA protocol is the one with the worst values. This happens as there are more collisions than in the other tested protocols and thus, as a collision occurs, in the best case, only one of the colliding packets can be decoded successfully by a GW, according to the collision model. Therefore, the EDs with better communication quality with a GW are more likely to succeed in their transmissions, which makes the network unfair, as the EDs that have better quality of signal with the GWs are in advantage. Regarding both RTS v2 variations, there is an improvement in the network fairness, comparatively to pure-ALOHA, as the use of control packets reduce the packet collisions, allowing the EDs with worst quality of signal with the GWs to have a better chance to transmit successfully. RTS v2 with 50 BS has a better fairness than the 100 BS version, for all tested networks, as it gives more opportunities for the EDs to transmit than when the contention is greater, even if they are in a zone with a low signal quality with the GWs.

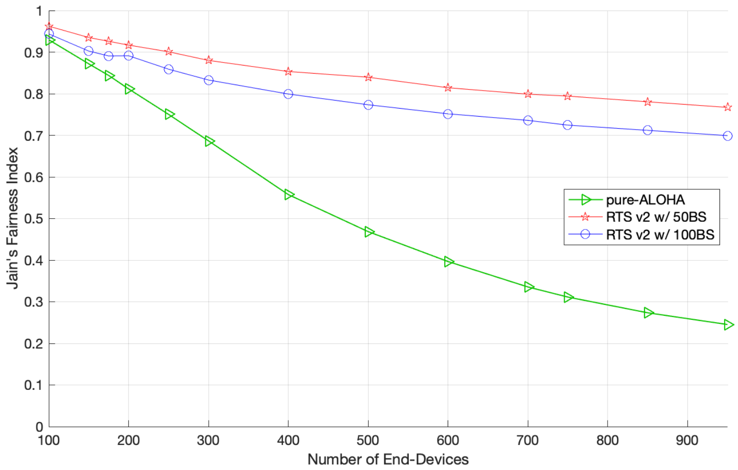


Figure 3.12: Network fairness of the RTS v2 and pure-ALOHA protocols for different network sizes.

3.4 Final Remarks

This chapter presented both the pure-ALOHA and the RTS protocols, being the difference between them the usage of control packets that advertise subsequent data packet transmissions. In the following, the reader was introduced to the simulation environment and the evaluation metrics. Next, a performance comparison between the two versions of the RTS protocol was presented, followed by a performance comparison between both pure-ALOHA and RTS protocols. As expected, the protocol that uses control packets achieved a better goodput, as the network grows, due to the decreasing number of collisions, as well as an increase in the network fairness, as the EDs with worst communication conditions have a better chance to transmit their packets.

Chapter 4

Dynamic Channel Protocols

In the protocols presented before, the communication parameters used by EDs and GWs were always the same, characterized by their long range and low communication rates, even if the signal quality with the GW was good. Now we are going to evaluate the performance of the LoRa network with the EDs parameterized differently, according to the communication quality they have with the single-channel GWs. This allows communication parameters to be more appropriate given the network context of the transmitting ED. To do so, a new MAC protocol is presented, the Channel Hopping protocol, where each ED is able to choose between different channels according to its RSSI value regarding to target GWs.

Section 4.1 explains the concept of *ideal channels* for EDs, relatively to a given GW, that could be used to transmit data packets in a more efficient way. Also, it explains the major differences between the three different channels that can be used by the network nodes, as well as how each one of them is assigned to a given ED. Section 4.2 gives a brief overview of the Channel Hopping protocol, and Section 4.3 details it, referring the behavior of the network elements, namely the EDs and GWs, in the different situations that occur during the network communications. Section 4.4 presents the three different versions of the Channel Hopping protocol tested in this dissertation, where the EDs behave differently during their execution. Section 4.5 presents an analysis of the results obtained with the different versions of the new protocol with respect to the static channel protocols presented in the previous chapter. Section 4.6 concludes the chapter.

4.1 Ideal Channels

In the Channel Hopping protocol, to be introduced in this chapter, the communication parameters used by the network elements are not always the same, varying according to the transmission conditions. Each combination of communication parameters allows the EDs to transmit in specific orthogonal channels, with more or less communication range and more or less data rate. So, there are different channels from which the network elements can choose. Each one of them covers up a group of EDs that have similar communication conditions with a given GW, enabling them to send the information faster than before, if the RSSI value is high enough, reducing the time spent in each transmission and decreasing the channel competition.

To address every ED communication situation, without increasing the complexity of the protocol, we chose three channels, each one with different characteristics, being them:

- **Fast-Rate Channel**: For EDs that have a good quality of signal with a GW, due to its short communication range capability. It is the faster of the three and so, the EDs that use this channel need less time to send a data packet. Consequently, they have to wait less time to comply with the mandatory duty-cycle restriction after every transmission, increasing the number of allowed transmissions;

- **Slow-Rate or Standard Channel**: For EDs that are within reach of a GW but have poor communication conditions with it. The ToA of the data packets is greater than in the other channels. This is the channel used by GWs to send synchronization packets, which will be introduced later in this chapter;

- **Mid-Rate Channel**: For EDs that have better communication conditions with a GW than the EDs that are in the Standard zone but worst than the ones in the Fast-Rate zone. The ToA of the data packets its greater than with the Fast-Rate channel, as a consequence of the greater communication reach.

In summary, when an ED has a good communication quality with a GW, it chooses the Fast-Rate channel to be its ideal channel, as it guarantees a higher transmission rate, without compromising the correct delivery of packets. The use of this operation channel will increase the network goodput, as the ToA is shorter, which leads to a decrease in the mandatory backoff time after each transmission. Thus, EDs are able to send the same number of packets than on the other two channels, using less channel time.

The EDs that have poor connection quality with a GW use the Standard channel as their ideal channel to transmit packets. This presents the slowest transmission rate and the longer range of the three, as referred before. Due to the later characteristic, it is the only channel in which the GWs transmit packets, namely synchronization ones, as it is important for them to reach as many EDs as possible.

Lastly, the EDs that have an intermediate quality of transmission with a GW, not as good as the EDs in the Fast-Rate zone nor as bad as the EDs in the Standard zone, choose Mid-Rate for their ideal channel. In this case, despite the quality of communication between the ED and GW is not as good as in the situation presented before, it covers a larger area of the network. The pay-off is the decrease in the transmission rate, making the transmissions slower when compared with the Fast-Rate channel.

In short, each ED has an ideal channel relatively to each GW that is on its range and so, for different GWs, EDs can have different ideal channels, seeking always to assign the one that guarantees the fastest possible transmission.

As different SFs are allocated to each channel, they are orthogonal and so, as said before, there is no interference between simultaneous transmissions using different channels.

4.2 Protocol Overview

The protocol proposed in this chapter, named Channel Hopping protocol, aims to change the LoRa physical parameters of EDs and GWs over time, so that packet transmissions occur in the most advantageous channel, avoiding the usage of a slower one when a faster could be used instead. Thus, EDs get to know which are their actual communication conditions with the GWs, in order to know the ideal channel to use when transmitting a packet to them. This information is obtained by EDs from a synchronization packet, the Change Mode (CM) packet, transmitted periodically, every time a GW changes from Standard to a non-Standard channel. So, with this packet, the GW informs EDs about which channel it will change to, how long will it stay using it and the communication quality, namely the RSSI value, between both of them, so that EDs can adjust their ideal channel.

The structure of the CM packet is shown in Figure 4.1. The base is the same as the one used in RTS packets, the only differences fall in the data field:

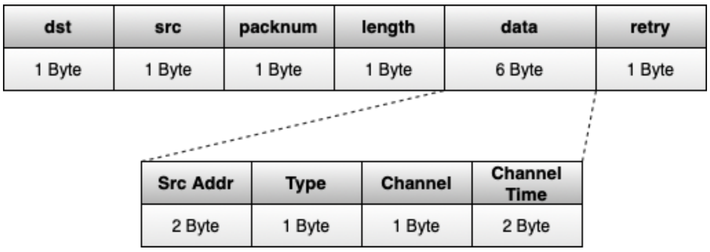


Figure 4.1: CM packet structure.

- **Src Addr** - Address of the node that sent the packet, so that the ED that overhears the CM packet knows from which GW this was sent;
- **Type** - Similar to the subfield with the same name in the RTS package, this indicates the type of the packet, that is a synchronization packet, namely a CM packet;
- **Channel** - This subfield indicates the channel the GW will change to, Mid-Rate or Fast-Rate channel;
- **Channel Time** - The Channel Time subfield contains information about how long the GW will spend in the advertised channel. This is crucial for the EDs to know exactly when the GW will return to Standard again.

Each ED adjusts its ideal channel, for each GW, based on the CM packets received from them, and gets to know when it can communicate with it using its ideal channel. Therefore, GWs will change their channel during their execution, to attend to the needs of all EDs that are in their reach. As the GWs have to comply with the mandatory duty-cycle restriction after every CM packet transmission, they cannot keep changing its operation channel any time they want. Therefore, the GWs follow a channel sequence, as shown in Figure 4.2. It should be noted that the cycle does not necessarily start with the Mid-Rate channel as shown. It can also be counted from the beginning of the Fast-Rate channel.

4.3 Protocol Description

This section explains in detail the operation mode of the base version of the Channel Hopping protocol. To do so, and to make the explanation clearer, the behavior of the EDs and GWs will be presented individually.

4.3.1 End-Devices

Every ED of the network begins in the Idle state, using the Standard channel, whether it is ideal or not. There, the EDs listen to the channel, in order to check if any of their

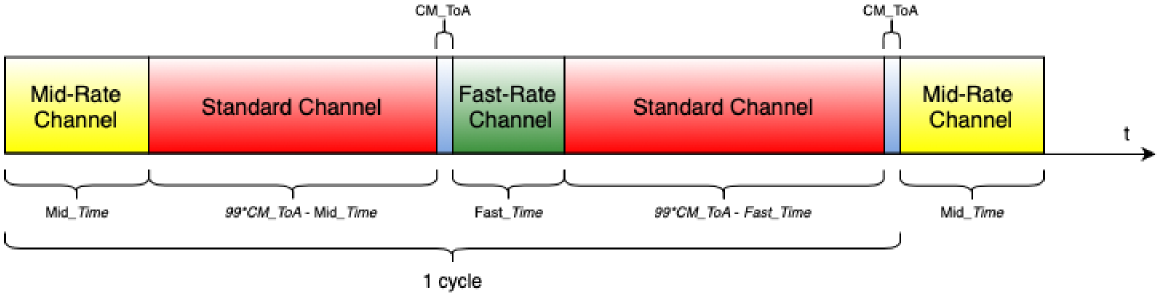


Figure 4.2: Channel Hopping protocol gateway cycle.

neighboring EDs intents to send a packet, advertised by an RTS packet, or even if the GW has sent a CM packet to advertise a change in its operation channel. In case it is overheard an RTS packet, the ED checks the intended GWs, as this information is contained in the RTS packet. Like what happens with RTS v2, if the data packet could be received by a GW on the communication range of the ED, the RTS packet should be considered. Otherwise, the ED should discard the overheard RTS and compete for the channel.

If, instead, the ED overhears a CM packet sent by a GW, it takes information from the CM packet about the communication quality with the GW, the advertised non-Standard channel, to which it will change to, and also the time that will remain on it. From that information, the ED updates, if necessary, its ideal channel, regarding the GW that sent the synchronization packet, and ensures that the advertised operation channel is its actual ideal one. If so, the ED changes its actual channel to the advertised one and competes to use the channel, knowing that, from that moment until the advertised time ends, the GW that sent the CM packet is able to receive its data packets. Otherwise, if the advertised channel is not its ideal channel, the ED checks if there is any other GW using its ideal channel, at the moment. If there is, the ED changes to its ideal channel, if not already using it, and competes for it.

This last described behavior, where the EDs check if any of the GWs in their reach are using their ideal channel, is also applicable when a GW changes from a non-Standard channel to the Standard one.

If there is really no GW operating in its ideal channel, the ED changes its channel to Standard, waiting for the next CM packet. Meanwhile, if Standard is not its ideal channel, it is not able to transmit any packet.

Each ED receives CM packets from, at least, one GW and knows when they will be sent next, in advance, as it is known that the GW sends a CM packet, periodically, every 30.4 seconds, approximately, that corresponds to the mandatory duty-cycle restriction that the GW must respect after sending a CM packet, using the Standard channel. So, to prevent the EDs to lose some CM packet, what implies not knowing which channel is being used by the GW, every ED forces its channel to be Standard as soon as a new synchronization packet will be sent by a GW of which the ED has already received a CM packet.

So, if the ED does not actually overhear any synchronization or control packet, has at least one data packet ready to be sent, has no time constraints and, at least, one GW in its reach is using its ideal channel, the ED will compete to use the channel in order to transmit a data packet. Therefore, first it sends an RTS packet to advertise the EDs on its range about its intent, so they can back off, and do not interfere in the transmission.

After transmitting the RTS packet, the ED transmits the data packet. After that, it calculates the mandatory backoff time that must take, so to respect the duty-cycle restrictions, based on the ToA that the RTS and data packet, combined, spent to be transmitted. To that value, it is added a contention window following a random number of backoff slots, which have the same duration as an RTS packet. Thus, in this protocol, the backoff time calculated after every data packet transmission is given by

$$\text{Backoff} = \text{Mandatory\_Backoff} + (randi([0,\ n]) * ToA(\text{RTS\_Size}, \text{Used\_Channel})),$$

where n represents the maximum number of backoff slots, RTS_Size the length of an RTS packet and Used_Channel the channel used to transmit the packets. Mandatory_Backoff is the mandatory backoff time that the ED must wait after every transmission, corresponding to ninety-nine times the ToA of the RTS and the data packets summed together.

Then, as it has to wait some time until it can send a data packet again, goes to the Backoff state and remains there for the remaining backoff time, jumping to the Idle state as soon as the restriction time ends. During its stay in the Backoff state, the ED continues to listen the channel and, if necessary, it updates its backoff time to do not interfere with any other transmission. This update is just done when the remaining backoff time is shorter than the time that the advertised data packet takes to be sent. During this state the ED also overhears synchronization packets sent by the GWs, to update its ideal channels.

Regarding the insertion of EDs in the network, as they have not yet received any CM packets, they do not know which channel the GWs in their reach are operating. Thus, before they start accessing the medium for transmission, they have to wait for the equivalent of a complete gateway cycle in the Standard channel in order to receive at least one CM packet from each GW and, thus, stay in sync with them.

The behavior of the EDs when they are in Idle and Backoff states is shown in Figures 4.3 and 4.4, respectively.

4.3.2 Gateways

Every GW starts its execution in the Idle state, using the Standard channel. There, it listens to the channel, receiving data packets sent by EDs that are actually using the same channel of operation. As soon as a GW checks that the time spent in a certain channel has ended, it proceeds to change it. If the channel in use is the Standard, the change is for a non-Standard channel, as follows: if the last change was from Standard to Mid-Rate channel, now the change will be to Fast-Rate channel, and vice-versa. This change is advertised through a CM packet transmitted in broadcast, so that all EDs in its reach are able to receive it.

On the other hand, if the operation channel in use is not Standard, it will change its channel back to Standard, without sending any CM packet, as the EDs already know that from a previous CM packet.

The described behavior of the GWs using the Channel Hopping protocol is shown in Figure 4.5.

4.4 Versions of the Channel Hopping Protocol

From the base version of the Channel Hopping protocol, which was presented before, two new versions were developed. They differ from the base version in terms of the used channel, in which the EDs send their packets and in the filtering of RTS packets overheard by the EDs.

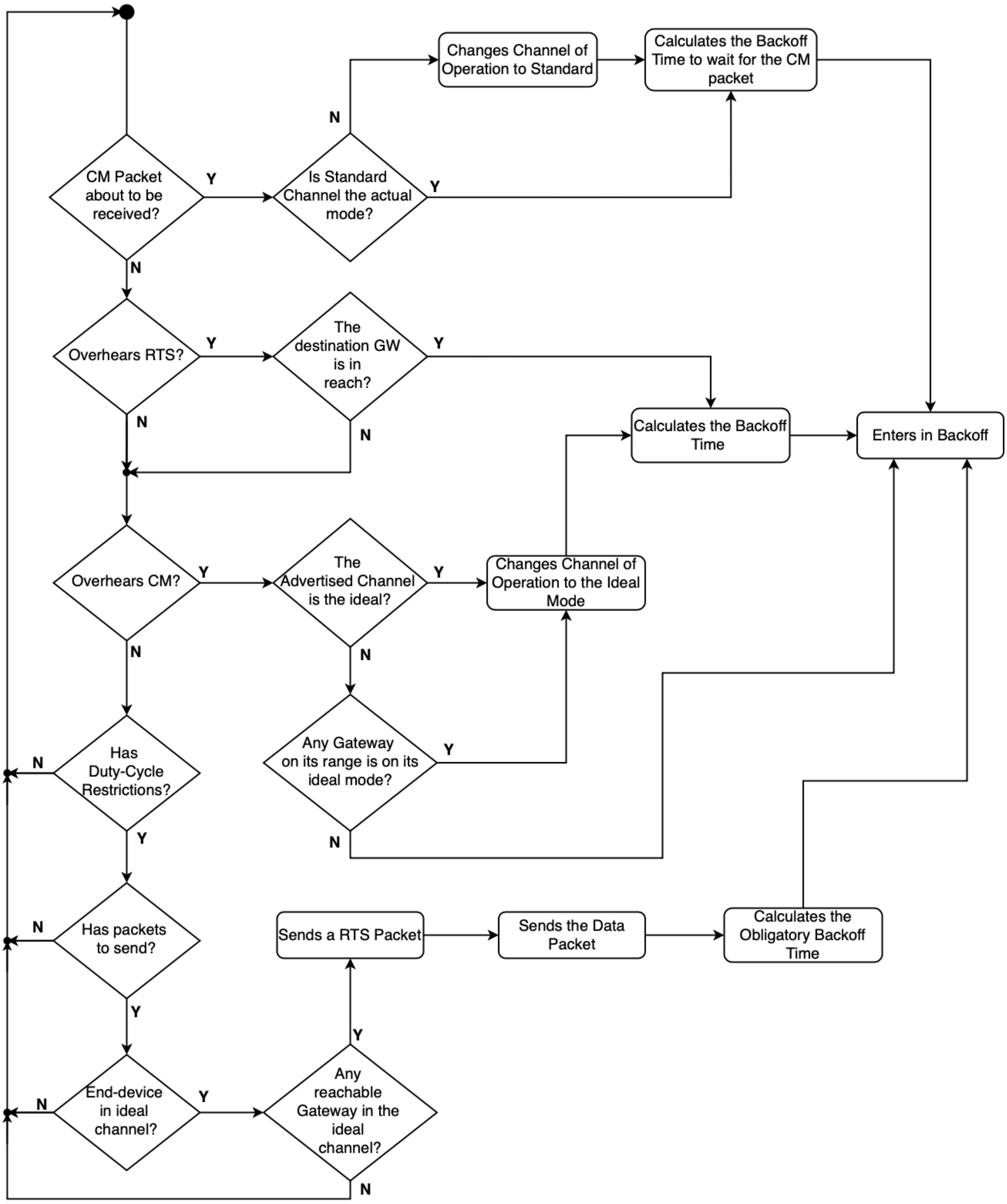


Figure 4.3: ED state machine in idle state for the Channel Hopping Protocol.

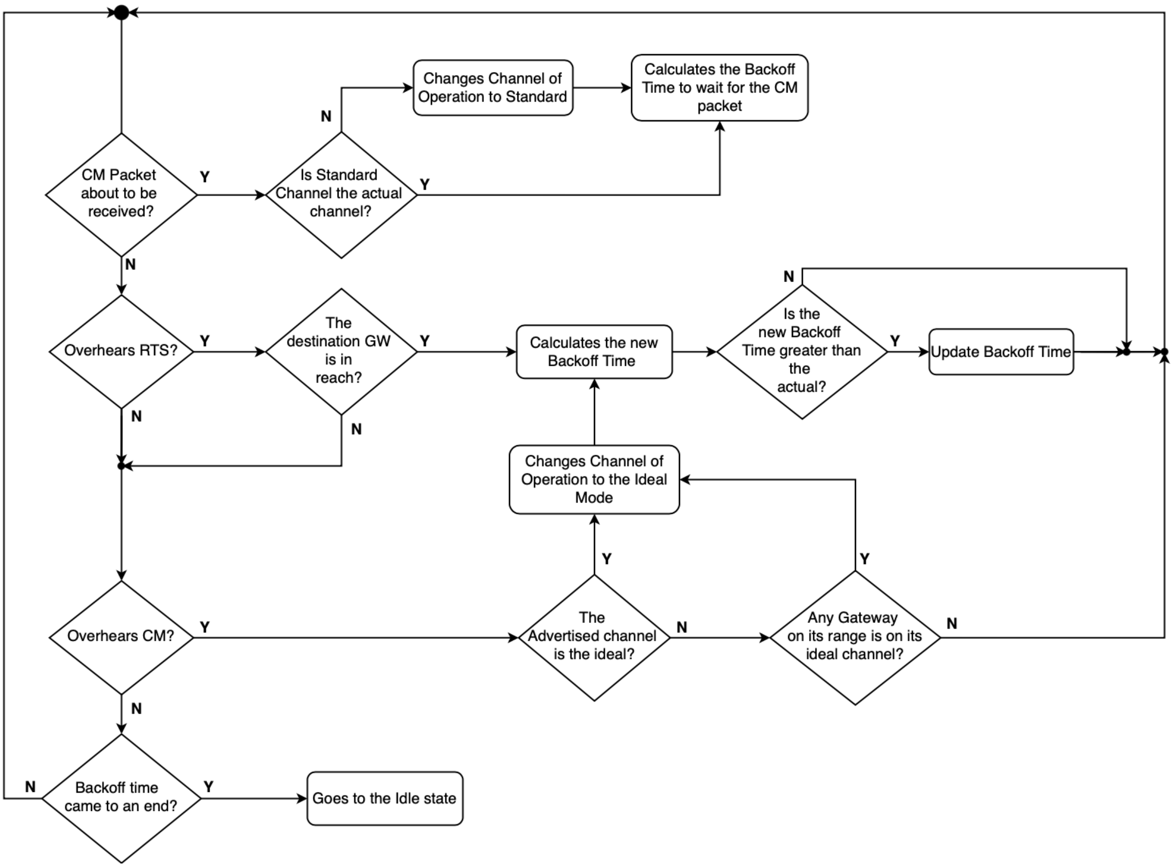


Figure 4.4: ED state machine in backoff state for the Channel Hopping Protocol.

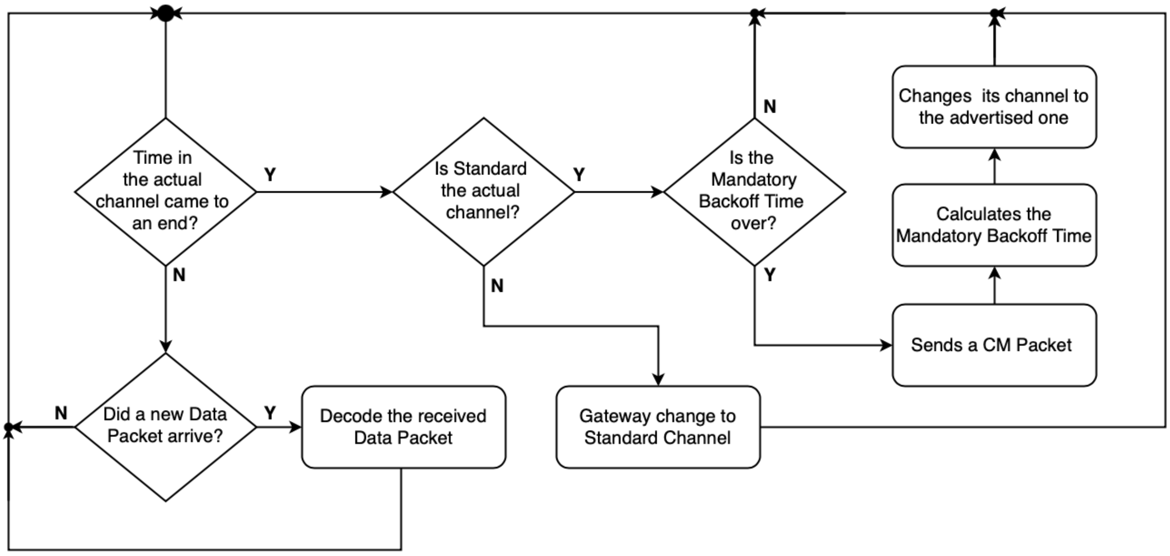


Figure 4.5: GW state machine for the Channel Hopping Protocol.

The designation of the three versions of the protocol are in the following:

- **Channel Hopping - Ideal Channel (CH-IC)**, the Base Version explained before;
- **Channel Hopping - Most Ideal Channel (CH-MIC)**;
- **Channel Hopping - Most Ideal Channel Filtering (CH-MICF)**.

Now, each one of these versions will be presented and explained in detail. Each explanation follows the LoRa network shown in Figure 4.6, with an overlap zone. In the figure, the green and black crosses are the gateways GW1 and GW2, respectively, and the blue circles the EDs. The red circumferences delimit the zones of each GW where the EDs have the same ideal channel in relation to it. So, the circumferences limit the Fast-Rate, Mid-Rate and Standard zones of the GWs from the smallest to the largest radius, respectively. Thus, all the EDs within a certain zone of a GW have the same ideal channel to communicate with it.

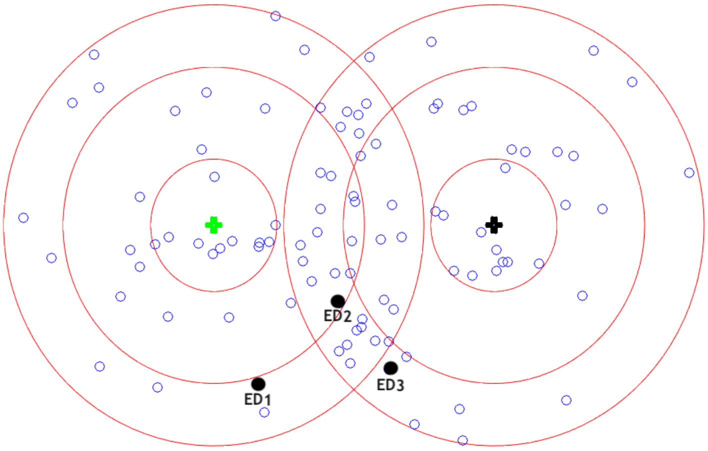


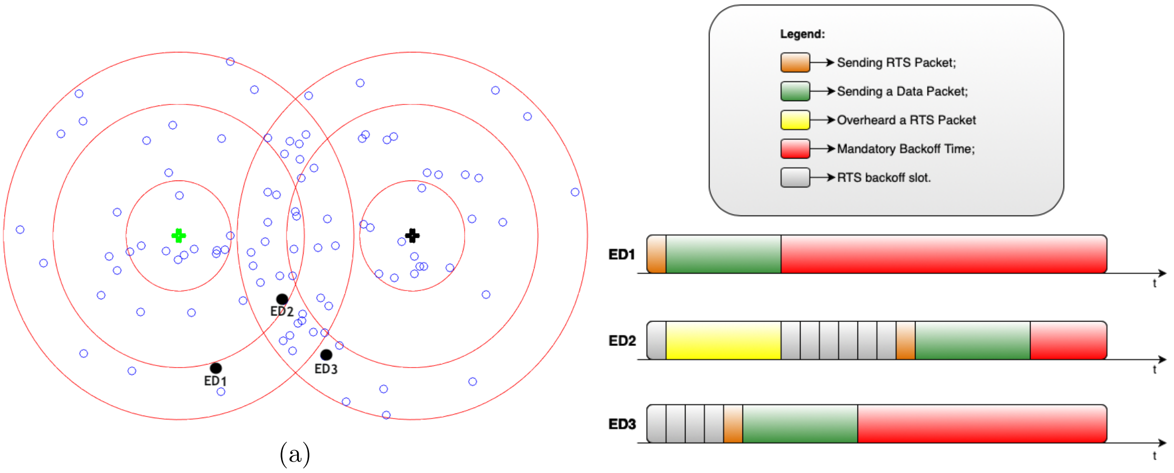
Figure 4.6: LoRa network with 100 EDs, from which 4 are referenced as ED1, ED2 and ED3.

4.4.1 Channel Hopping - Ideal Channel (CH-IC)

The first version, presented above, is called Channel Hopping - Ideal Channel (CH-IC). It is the base version of the Channel Hopping protocol and so, its behavior is exactly the one described in section 4.3, without any change whatsoever.

Figure 4.7 shows the behavior of the EDs ED1, ED2 and ED3 operating in a LoRa network with two gateways, GW1 and GW2, similar to the one shown in Figure 4.6.

Thus, ED1 sends an RTS packet in order to advertise a data packet transmission. This control packet is overheard by ED2 and ED3. But, because ED3 has only GW2 in its reach, and the advertised data packet could only be received by GW1, the control packet is discarded. ED3 knows that as the overheard RTS packets contains that information, based on the last CM packets received by ED1. So, with this, ED3 avoids the backoff, being able to compete for the channel to send a data packet, without interfering with ED1's packet. With this filtering of the RTS packets, the network performance is expected to increase, as the EDs avoid unnecessary backoff times and thus, access the channel more often, avoiding to remain for too long without transmitting.



(a)

(b)

Figure 4.7: LoRa network with three EDs marked in black (a), whose behaviour is analyzed with CH-IC protocol (b).

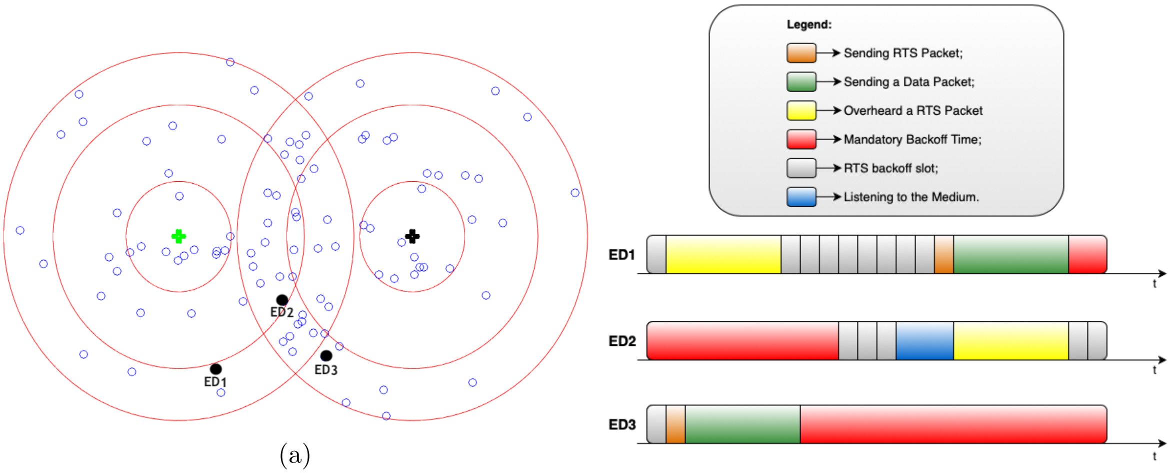
ED2, on the other hand, as it is in reach of both GWs, as soon as receives the RTS packet from ED1, backs off for the duration of the advertised data packet, represented in yellow, added to a random number of RTS packet slots, represented in Figure 4.7 in grey. When the RTS packet sent by ED3 is received by ED2, it still has a backoff time left to wait that is greater than the ToA of the advertised packet and so, it does not update its backoff time. In case the time left to wait is smaller than the duration of the ToA of the advertised packet, ED2 would have to update its backoff time.

4.4.2 Channel Hopping - Most Ideal Channel (CH-MIC)

The second version developed is called Channel Hopping - Most Ideal Channel (CH-MIC). This new version, unlike the previous one, only allows the EDs to send data packets using the fastest channel possible.

This means that, if an ED is located in the overlap zone and has different ideal channels relatively to both GWs, it can only transmit using the channel with the best quality of communication. Thus, the transmission is done faster, as the ToA of the packets is smaller. For example, if the considered ED's ideal channels to communicate with the GWs 1 and 2 are Standard and Mid-Rate channel, respectively, the ED only uses the Mid-Rate channel to transmit data packets. Therefore, only sends data packets to GW2, considering that its location in the network, relatively to the GWs, never changes and the ideal channel, consequently, stays the same throughout its execution. The EDs located in the overlap zone can only send packets to both GWs when the ideal channel is the same for both of them.

Figure 4.8b represents the behavior of the ED1, ED2 and ED3, represented in Figure 4.8a, using CH-MIC protocol. Knowing that, as in this version of the protocol each ED only sends data packets when it is using its fastest ideal channel possible, ED2, as it has two different ideal channels for each GW, only uses Mid-Rate channel, the one that allows the fastest data rate. Thus, even if ED2 is in Standard channel, as well as the GW2, it does not send data packets. Instead, awaits for a channel change by GW1 to the Mid-Rate channel. Despite this, ED2 when in the Standard channel, continues to listen to the RTS packets sent by other EDs



(a)

(b)

Figure 4.8: LoRa network with three EDs marked in black (a), whose behaviour is analyzed with CH-MIC protocol (b).

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that are on the reach of the GW2, without discarding them.

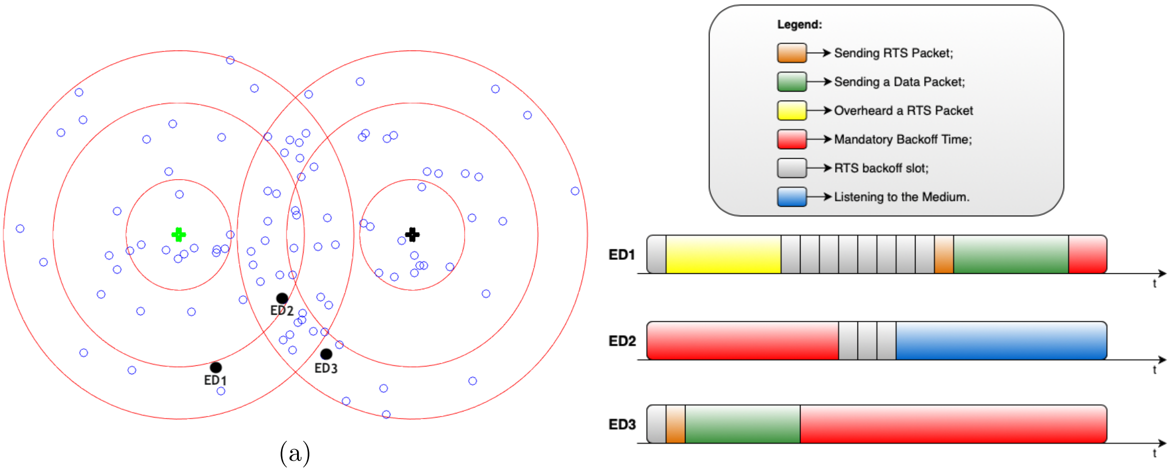
In the considered time frame, both GWs are operating in Standard channel, so as the three reference EDs. As shown in the timeline of ED2, instead of sending a data packet after its backoff time came to an end, it remained listening to the channel, waiting for GW1 to change to the Mid-Rate channel, the only channel with which it transmits data packets.

Observing the behavior of ED1 and ED2, ED1 receives an RTS packet, that is not received by ED3 and ignored by ED2, as the new backoff time is lower than the actual one. This means that the transmitting ED is in the Standard zone of the GW1, too far from the overlap to reach ED3. It is true that, even if ED3 had overheard the packet, would have discarded it. So, ED1 updated its backoff time and, at the end of that, managed to send its data packet only because, as referred before, ED2 did not access the channel. If the protocol used was the CH-IC, would have been ED2 to send its data packet instead of ED1, as its backoff time ended first and the GW1 was in its ideal channel.

4.4.3 Channel Hopping - Most Ideal Channel Filtering (CH-MICF)

The Channel Hopping - Most Ideal Channel Filtering, CH-MICF for short, is the third version of the Channel Hopping protocol and the difference lies in the process of filtering the RTS packets. So, CH-MICF protocol goes beyond the filtering method of the previous versions; the EDs not only discard RTS packet when they are advertising a data packet that could only be received by GWs that are not in their reach, but also when the received RTS packet is sent in other channel than its fastest ideal one. This process does not cause data packet loss, due to collisions, as EDs only send packets when using their fastest ideal channel, and allows the EDs to be ready to compete for the channel, as soon as the channel change occurs.

Figure 4.9 represents the behavior of the EDs using the CH-MICF protocol, knowing that the location and ideal channels of the EDs are the same as those used in the CH-MIC protocol. This time, ED2, instead of having considered the RTS packet sent by ED1, represented in orange, keeps listening to the medium, waiting for a channel change from any of the two



(a)

(b)

Figure 4.9: LoRa network with three EDs marked in black (a), whose behaviour is analyzed with CH-MICF protocol (b).

GWs. This procedure is due to the new filtering feature, that allows the EDs to discard RTS packets that were not sent in their fastest ideal channel. That way, in this case, ED2 only considers RTS packets that are sent in Mid-Rate channel. With this, as soon as the GW1 changes back to Mid-Rate channel, it can access to the medium without having to wait for a data packet sending that it is occurring in other channel and there is no problem of occurring simultaneously, as they being performed using different channels.

With this version of protocol, it is expected a better goodput, as the EDs do not have to back off unnecessarily, and thus, have more opportunities to transmit.

As a summary, Table 4.1 shows the improvements of each version of the Channel Hopping protocol, compared to the protocol on which they were based.

Table 4.1: Summary of Channel Hopping protocol versions.

Protocol	**Base Protocol**	**Improvement(s)**
CH-IC	RTS v2	- Introduction of channel hopping, instead of a static one; - Each ED transmits using its ideal channel relative to the GW.
CH-MIC	CH-IC	- Each ED transmits only on its fastest ideal channel.
CH-MICF	CH-MIC	- Each ED filters the control packets, discarding those that were not transmitted on their fastest ideal channel.

4.5 Protocol Comparison

In order to check the improvements achieved with the increased complexity from protocol to protocol, this section evaluates the several MAC protocols, ranging from the RTS v2 with 50 BS, up to the CH-MICF. It is expected that the CH-MICF, being the most complex one, presents the best overall performance since its features allow the EDs to send packets only when using the fastest channel possible and to manage the overheard RTS packets in a more selective way, avoiding unnecessary waiting time that harms the performance of the network.

4.5.1 Simulation Environment

The simulation environment used for testing the Channel Hopping protocol is very similar to that presented earlier in Chapter 3. The only difference is the distinction between zones of the network related to the channels.

In Figure 4.10, the blue and black crosses are the gateways GW1 and GW2, respectively, and the blue circles are the EDs. Each one of the red circumferences centered on the GWs represents the maximum limit of communication to the gateway given a specific channel. Counting from those with the smallest to the largest radius, they define the maximum distance that EDs can be from each GW to send their packets with Fast-Rate, Mid-Rate and Standard channels, respectively. Therefore, new zones of the network are now considered related to the channel used by the EDs whose location is there. So, the zone whose distance from the GW is less or equal than the limit of the smaller circumference is called the Fast-Rate zone, between the smallest and intermediate circumferences is the Mid-Rate zone and between the intermediate and greater ones is the Slow-Rate or Standard zone.

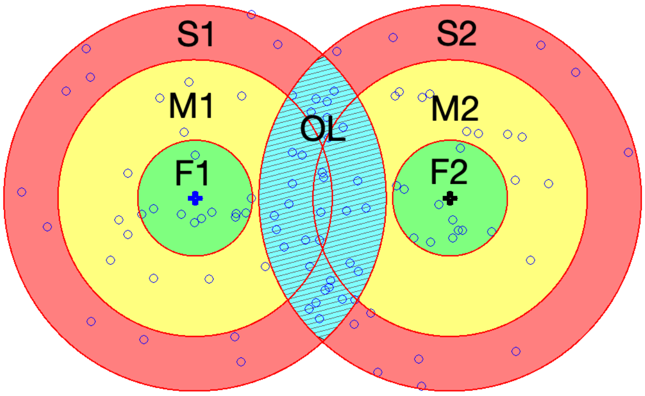


Figure 4.10: LoRa network with 100 EDs and two gateways, GW1 and GW2 shown as a blue and black cross, respectively. Red represents the Slow-Rate zones of GW1 and GW2 (S1 and S2), yellow the Mid-rate zones (M1 and M2) and green the Fast-Rate ones (F1 and F2). The intersection of more than one zone of different GWs is the overlap zone, the cyan area with hatch fill (OL).

Regarding to the dimensions of the network, relatively to the maximum range for every channel, we assumed the results achieved by Oliveira *et al.* [31] in Alqueidão, a rural village without big buildings that may obstruct the signal. The ranges used for each channel are in Table 4.2.

Table 4.2: Maximum reach and RSSI values for each channel.

	Range (m)	**RSSI Range (dBm)**
Fast-Rate	1210	[-100 -90]
Mid-Rate	2890	[-110 -101]
Slow-Rate	4030	[-125, -111]

The EDs were distributed by the different zones of the network in the following way:

- **GW 1 Standard (Slow-Rate) Zone (S1)**: 1/9 of the total number of EDs;
- **GW 1 Mid-Rate Zone (M1)**: 1/9 of the total number of EDs;
- **GW 1 Fast-Rate Zone (F1)**: 1/9 of the total number of EDs;
- **Overlap Zone (OL)**: 1/3 of the total number of EDs;
- **GW 2 Standard Zone (S2)**: 1/9 of the total number of EDs;
- **GW 2 Mid-Rate Zone (M2)**: 1/9 of the total number of EDs;
- **GW 2 Fast-Rate Zone (F2)**: 1/9 of the total number of EDs.

As happened in the tests performed in Chapter 3, as the map of EDs used is the same, each GW has only in its exclusive reach 33% of all EDs and the remaining 33% are in the overlap zone, reachable by both GWs. Regarding those which are only in reach of one GW, they are distributed by the three zones in an equal way, *i.e.* 33% per zone. For networks where the division of the total number of EDs by the three generic zones, within reach of both or just one GW, does not return an integer number, the overlap zone gets more or less one ED, as well as the Mid-Rate zone if the division of EDs by the zones that define the communication channels is also a decimal number. Table 4.3 shows how many EDs are placed in each zone of the network according to the total number of EDs in the network that were tested. When evaluating the Channel Hopping protocols, it was chosen a Mid-Rate channel of 10 seconds and a Fast-Rate channel of 7.5 second, per cycle, respecting the diagram of Figure 4.11. In the next chapter it is addressed the impact of such times. Each half-cycle has the duration of the mandatory restriction, corresponding to ninety-nine times the ToA of a CM packet, added to the ToA of a single CM packet transmission. Considering that each CM packet has a size of 11 bytes, the restriction time is equal to, approximately, 30.4 seconds. So, one

Table 4.3: Number of EDs per zone of the network, considering the three zones, one for each channel used, that are only are in reach of one GW and the Overlap zone, in reach of both GW.

#EDs	Slow-Rate Zone	Mid-Rate Zone	Fast-Rate Zone	Overlap Zone
100	11	11	11	34
150	17	16	17	50
175	19	20	19	59
200	22	23	22	66
250	28	27	28	84
300	33	34	33	100
400	44	45	44	134
500	56	55	56	166
600	67	66	67	200
700	78	78	78	234
750	83	84	83	250
850	94	95	94	284
950	106	105	106	316

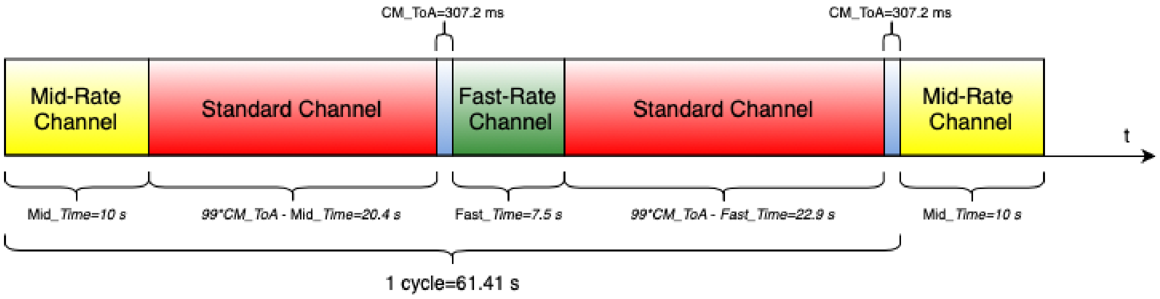


Figure 4.11: Channel Hopping protocol gateway cycle.

cycle lasts for, approximately, 61.4 seconds and the GW switches between the three available channels, alternately.

The use of RTS packets is kept, being received only by the EDs using the same channel as the transmitting ED. Table 4.4 presents the ToA of control packets on the different channels. The configuration parameters for each channel can be found in Table 4.5.

Table 4.4: ToA of each control packet.

	Standard Channel	**Mid-Rate Channel**	**Fast-Rate Channel**
RTS Packet	286.55 ms	75.52 ms	12.39 ms
CM Packet	307.05 ms	-	-

Table 4.5: Radio parameters of each channel.

	BW (kHz)	**CR**	**SF**	**Sensitivity (dB)**
Standard Channel	125	4/5	10	-129
Mid-Rate Channel	250	4/5	9	-123
Fast-Rate Channel	500	4/5	7	-114

4.5.2 Goodput Analysis

As can be seen in Figure 4.12, the goodput of the CH-MICF outperforms all the other schemes, for all tested networks. This occurs because in this protocol, unlike the other two Channel Hopping versions, EDs only consider overheard RTS packets that have a direct influence on their transmissions. Thus, this feature allows EDs, when not in their fastest ideal channel, to be always ready to transmit data packets, as soon as a GW in their reach changes its channel to the desired one. Figure 4.13a shows an increase in the number of accesses, mainly from EDs close to the overlap zone. Therefore, a greater number of data packets is transmitted to the GWs, value that is mirrored in the goodput results. In the other protocols, the RTS packets are only discarded if the GW, or GWs, that are able to receive the advertised data packets are not in the reach of the ED that overheard it, without any confirmation if the control packet was sent in the fastest ideal channel of the ED, as happens in the CH-MICF protocol. Thus, an ED in that situation had to back off and, if one of the GWs in its reach changes the channel to its ideal one, it would not be ready to send a data packet right away. Therefore, this explains why CH-MIC protocol, where the EDs only use

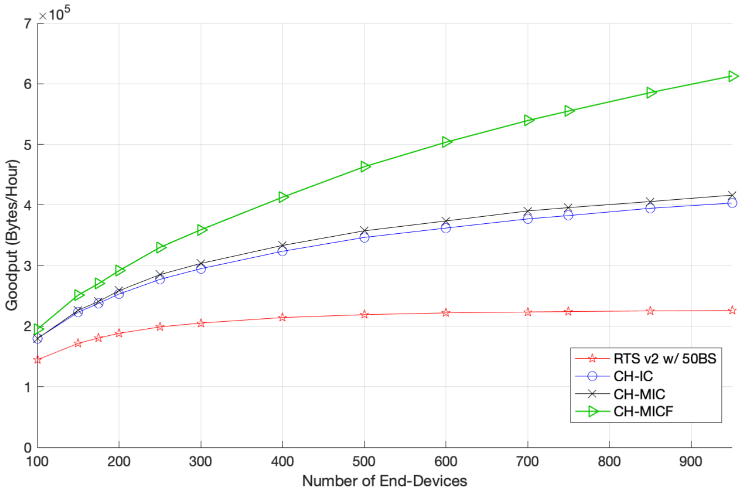
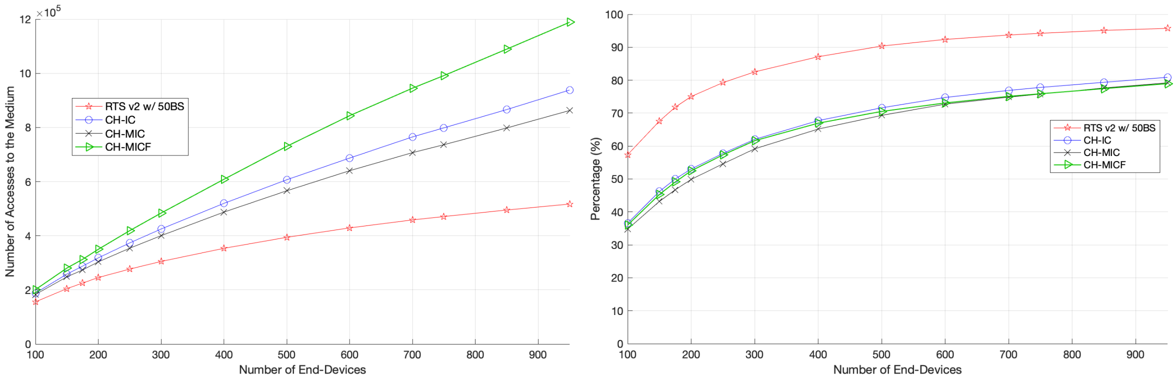


Figure 4.12: Goodput of RTS and the Channel Hopping protocols for different network sizes.



(a) (b)

Figure 4.13: Number of medium accesses by the EDs (a) and percentage of collisions (b) of RTS v2 and the Channel Hopping protocols for different network sizes.

their fastest ideal channels, has less accesses to the medium than CH-MICF. Also, CH-IC presents a greater number of accesses than CH-MIC, as the EDs can transmit in any of its ideal channels, having more opportunities to do so.

Regarding the goodput of the two other Channel Hopping protocols, the CH-MIC, despite the smaller number of accesses to the medium, achieved better values of goodput than CH-IC, as each ED only transmits when using the fastest possible channel, resulting in less channel access competition and thus, a lower percentage of packet collisions, as shown in Figure 4.13b.

As the network has one zone that is concerned to both GWs, it should be expected that the same packet could be received by both of them, as they can be using the same channel, at the same time, resulting in a number of duplicate data packets. The existence of duplicate data packets can reduce the quantity of lost information due to data packet collisions, as the same packet could not reach successfully one of the GWs and be successfully decoded by the other one. However, receiving two data packets that are exactly the same can also affect the goodput of the network, as a data packet that reached successfully both GWs could prevent another packet, with distinct information, to be recovered by one of them.

As shown in Figure 4.14, as in the RTS protocol the GWs always use the same channel, the overlap EDs are always able to communicate with both GWs, and thus the number of times that both GWs are able to receive the same packet is higher than for the other protocols. However, as the network grows beyond 750 EDs, CH-MICF and CH-MIC, which values are very similar, outperform RTS v2, as the competition to access the medium is more reduced, allowing the EDs on the overlap zone to access the medium more often, and, in some cases transmit their packets faster. On the other hand, CH-IC protocol registers the lowest number of situations to be possible for both GWs to receive the same data packet, as the overlap EDs are able to transmit using any of their ideal modes, even if it is not the fastest one. Thus, there are more EDs competing to use the Standard channel, which causes a decrease in the number of opportunities to send duplicated packet, in addition to having a higher occurrence of collisions. Despite that, as the network scales up, the difference between the opportunities of the RTS v2 and CH-IC protocols become smaller, as the number of EDs competing to access the medium is higher in the RTS protocol and so, the overlap EDs have less chances to transmit packets. Figure 4.15a shows the percentage of duplicate data packets received at both GWs. The RTS protocol is the one with the lowest values, due to the higher number of EDs accessing to the medium at the same time, as the Standard channel is the only one. On the other hand, in every Channel Hopping protocol, as there is less access competition, the percentage of packets that could be received by both GWs is higher than in the RTS protocol, suffering a decrease as the network grows due to the increase of the collisions. The CH-IC is the one with the worst percentage values, as the data packets are not always sent in the fastest channel possible and the number of EDs competing is higher than in the other Channel Hopping protocols.

On the other hand, a packet intended to be received by both GWs can only be received by one of them, as shown in Figure 4.15b that represents the amount of packets in the described situation. According to the presented results, the RTS starts to be the protocol with the lowest amount of occurrences, followed by CH-IC, CH-MIC and CH-MICF, with very close results. As the network scales up to 950 EDs, the RTS protocol becomes the one with the biggest amount of packets received by at least one GW, the opposite of what happens when only

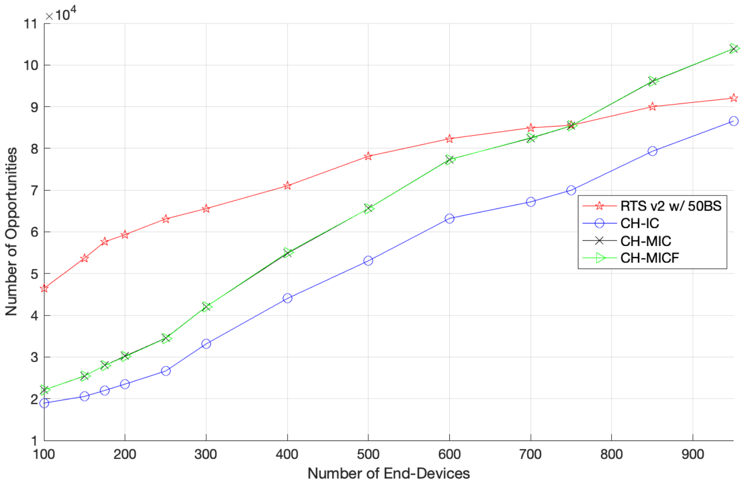
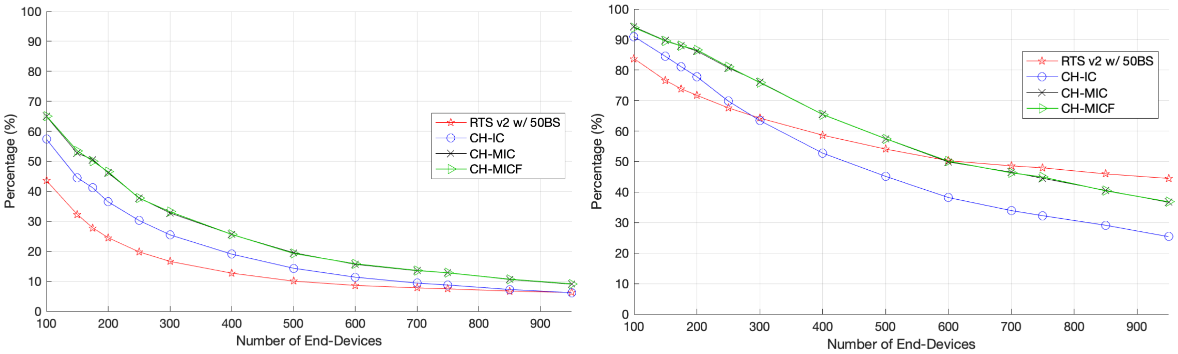


Figure 4.14: Number of times that the transmissions could be recovered by both GWs of the network for RTS v2 and the Channel Hopping protocols.



(a) (b)

Figure 4.15: Percentage of duplicate data packets, considering all the sent data packets that could be received by both GWs, at the moment, received successfully by both of them (a) and by, at least, one of them (b) for RTS v2 and the Channel Hopping protocols.

duplicate packages are considered. Such behavior is explained because in the RTS protocol an overlap ED can have much better transmission quality relatively to one of the GWs and so, it is more likely for its packets to be delivered successfully. In the CH protocol this does not happen as the ideal channels are defined according to the link quality, between EDs and GWs.

Comparing the number of EDs in the overlap zone for the different evaluated scenarios, indicated in Table 4.3, with the fluctuations in the number of situations where duplicated packets could be originated, as both GWs are able to decode the same packet, the direct link between these two results is easily observed, especially for the protocols with channel hopping.

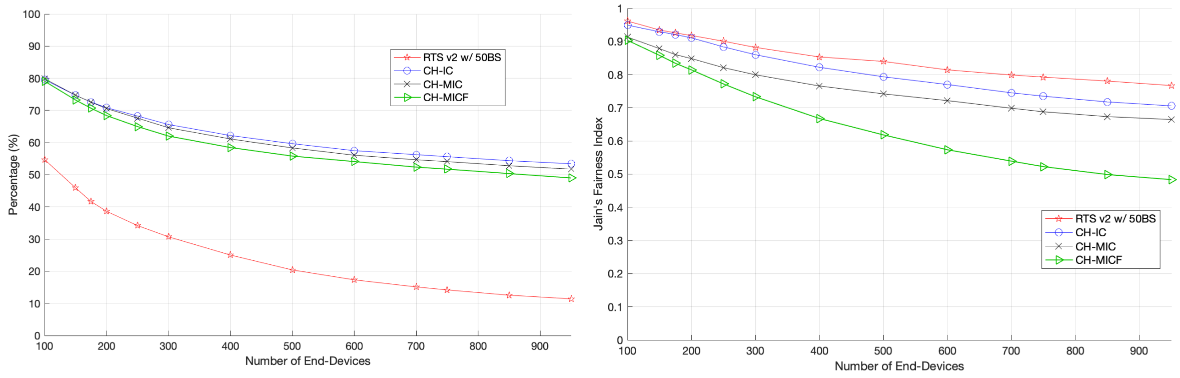
The number of collisions in the network are also a factor that influences the goodput of the system, as referred before. Thus, the lower the number of data packet collisions, the lower the useful information that is lost, which consumes time and energy. According to Figure 4.13b, the amount of collisions, per packet sent, is significantly lower in the Channel Hopping protocols, which corroborates with the increase in the network goodput.

Thus, from Figure 4.16a can be concluded that, with the introduction of channel hopping, the amount of data packets successfully delivered to a GW without having suffered a collision increases, when compared with the tested static channel protocol, from about 25%, for a network with 100 EDs, to about 37%, when the network scales up to 950 EDs. This is possible as the EDs, when accessing to the medium, have less EDs to compete with and so, the transmission is more likely to be done without any collision.

Regarding to the performance of the Channel Hopping protocols, it is very similar for both the CH-MIC and CH-MICF, being these better than the CH-IC.

4.5.3 Fairness Analysis

As the number of successfully delivered data packets increases, the network fairness of the CH-MICF protocol presents the worst values, as shown in Figure 4.16b. This happens because, as Figure 4.17 confirms, the EDs located in the Fast-Rate zone of each one of the GWs are able to send a greater number of data packets than the EDs in the other zones of the network. This occurs because the EDs with Fast-Rate as their fastest channel can send



(a) (b)

Figure 4.16: Percentage of recovered data packets that did not suffer a collision (a) and Jain's Fairness Index (b) of RTS v2 and the Channel Hopping protocols.

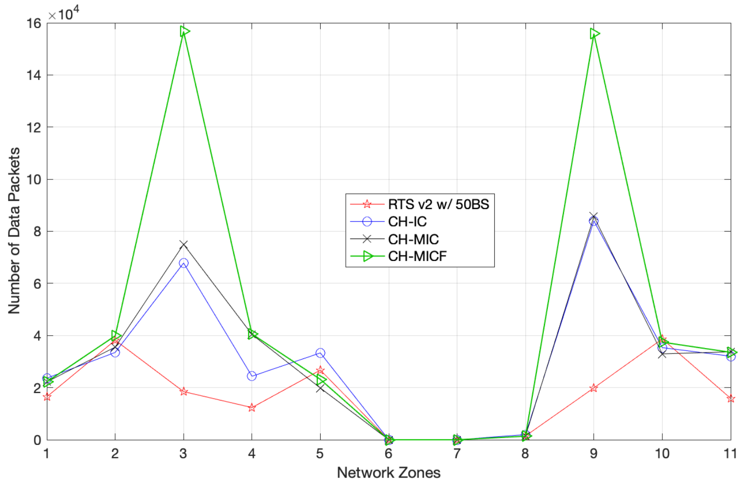


Figure 4.17: Number of successful transmissions of the EDs of each network zone for RTS v2 and the Channel Hopping protocols, when there are 950 EDs in the network. The explanation about the ID of each zone is in Table 4.6.

the same amount of information than the EDs that use other channels in less time and thus, the gap of data packets sent in the different zones will increase and the fairness of the network will come out impaired.

This unbalanced behavior is caused mainly by the GW time assigned to each channel, especially to the Fast-Rate one, since it is faster than the others, it should have less than 7.5 seconds, in order to increase the number of the received data packets using the other channels and thus, increase fairness. Although, it is noteworthy that this time manipulation will affect the goodput of the network, as the number of received packets will be reduced with the decrease of the Fast-Rate GW time.

As expected, the fairness of the CH-MIC is the second worst, as the network grows, because the EDs transmit their packets only on its fastest channel possible and, by consequence, the EDs that are able to transmit packets using Mid-Rate and Fast-Rate as their fastest, are able to access and transmit more packets than those which use the Standard channel, increasing

Table 4.6: Location of each Zone ID in the network. The zones that are located in the overlap zone, when represented with X, are in the same zone for both GWs.

Zone ID	**Standard zone**	**Mid-Rate zone**	**Fast-Rate zone**	**GW(s)**
1	X	–	–	1
2	–	X	–	1
3	X	–	X	1
4	X	–	–	1 *and* 2
5	X	X	–	1 *and* 2
6	–	–	X	1 *and* 2
7	–	X	X	1 *and* 2
8	–	X	–	1 *and* 2
9	–	–	X	2
10	–	X	–	2
11	X	–	–	2

the goodput gap between them. Therefore, the network fairness drops. The one protocol that provides a better fairness in the network is the RTS v2, as every ED is in the same channel and every one of them have exactly the same time to access the medium and the same time to transmit. Despite that, it is true that EDs that have a worst communication link with the GWs have a lower probability to successfully send packets to the GWs, harming the fairness with the network growth. This is followed by the CH-IC, with the second best performance, as in this protocol EDs do not use only the most ideal channel, relatively to a GW, whatever it is.

4.5.4 Zone Performance

This section analyses the performance of each network zone for the RTS and Channel Hopping protocols.

Regarding the RTS protocol, as shown in Figure 4.18, the zone with the highest aggregated goodput is overlap, as there are three times more EDs there than in the other zones. Regarding

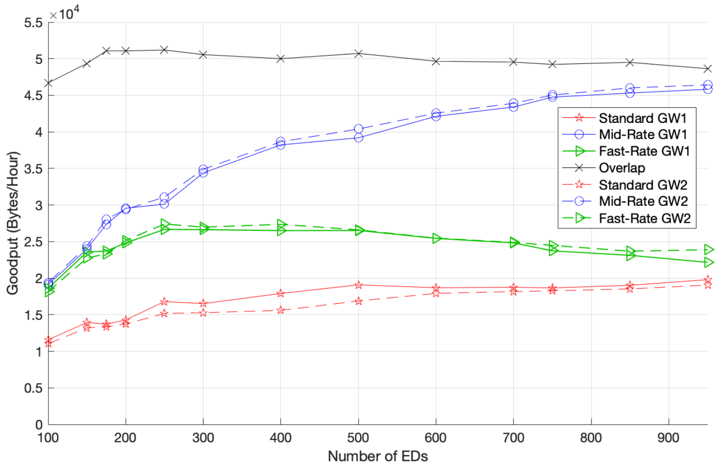


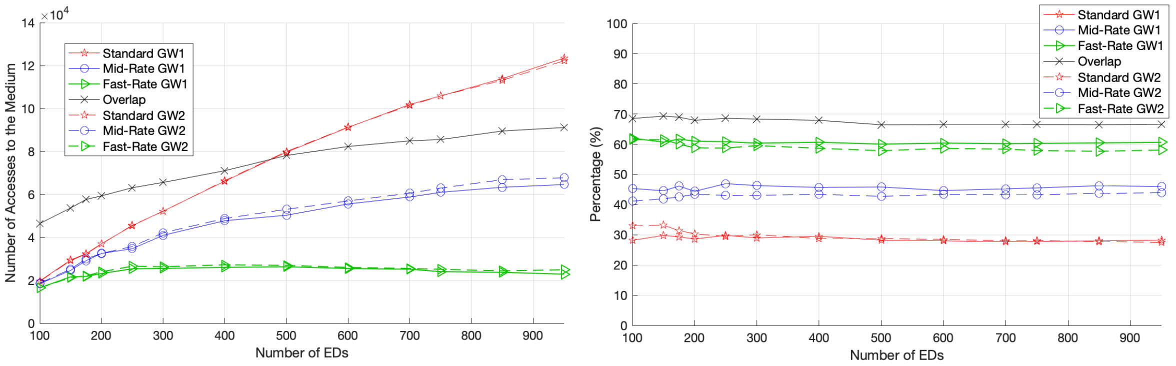
Figure 4.18: Aggregated goodput on each network zone with the RTS v2 protocol.

zones that are only on reach of one GW, Mid-Rate zone is the one that presents the best goodput. This is due to the balance between the quantity of neighboring EDs from which they receive RTS packets, and their signal quality to the GW. Despite the better quality of signal of Fast-Rate EDs, they are the ones that have less opportunities to access the channel, as Figure 4.19a portrays, because they receive, on average, more RTS packets from other EDs than the EDs located in the other single GW zones, as they are in reach of a higher number of EDs, as shown in Figure 4.19b. Figure 4.20 shows the networks with 950 EDs, which are represented in different colors according to the percentage of EDs that are on their reach of communication, using the RTS protocol. The legend that corresponds each ED color to the percentage interval of EDs that the ED is able to communicate with is shown in the Table 4.7. The percentages are based on the values shown in Figure 4.19b. Also in Table 4.7 is shown the percentage of EDs from each zone that are inserted in each level of overhearing. With the growth of the network, the goodput of the Fast-Rate zone decreases, as the number of RTS packets received by the EDs increases, preventing them from transmitting packets.

However, despite the poorer goodput, when the Fast-Rate EDs are able to access the medium they deliver successfully their data packets more often than the ones on the other network zones, as shown in Figure 4.21a, because they have a better connection with the GWs and thus, even if a collision occurs, they are very likely to be successfully delivered.

The Standard zone EDs are the ones with the poorer goodput due to the low percentage of data packets successfully delivered to the GWs, despite being the ones that, as the network scales, are able to access the medium more often. This is caused by the poor quality of signal that its EDs have relatively to the network GWs, presenting a low probability of successful communication if it collides with another one. In fact, according to Figure 4.21b, EDs on the Standard zone are the ones, on the range of a single GW, that delivered successfully less data packets. The zone that delivers, on average, less packets than Standard is Overlap, despite being the zone with the best overall goodput, as it is the zone with the highest percentage of RTS packets overheard by the EDs, as shown in Table 4.7. In this zone 88.61% of the EDs are on the first level of overhearing, level in which the EDs are able to overhear, at least, 60% of the network EDs.

Regarding the CH-MICF protocol, as shown in Figure 4.22, the goodput of the Fast-Rate zone is the best one, as the network grows. This is due to the fastest rate used by the Fast-



(a) (b)

Figure 4.19: Number of medium accesses (a) and the average percentage of EDs on the reach of each ED (b) in each network zone with the RTS v2 protocol.

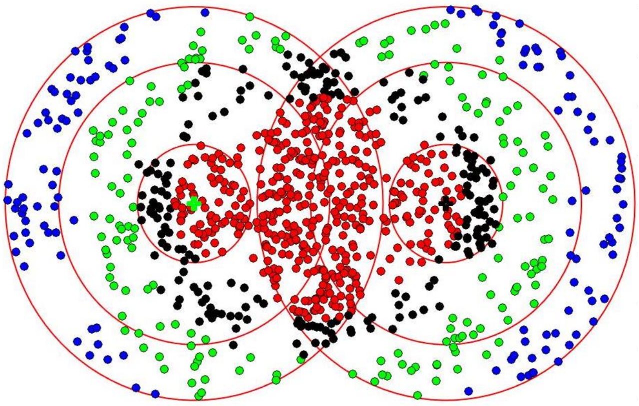
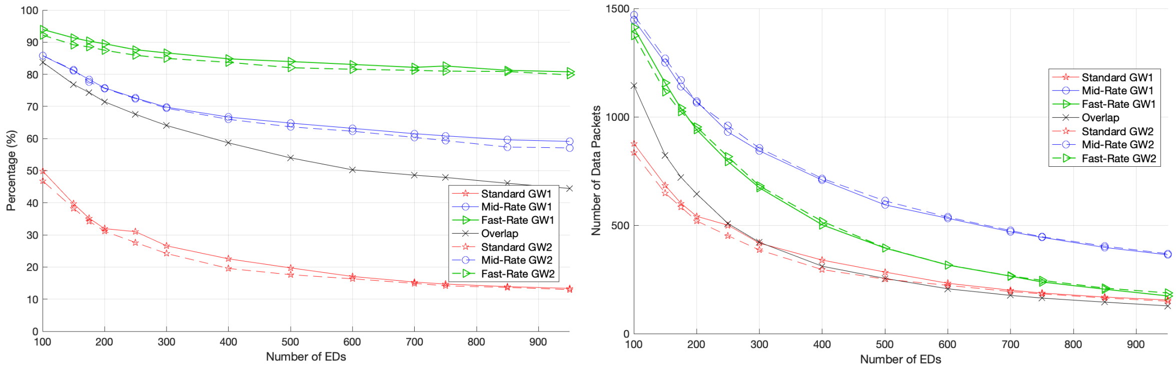


Figure 4.20: Network with 950 EDs colored according to the level of overhearing, explained in Table 4.7, and using the RTS v2 protocol.

Table 4.7: Relationship between the color and the level of overhearing. The percentage values in bold represent the maximum values for the respective network zone.

Level of Overhearing	Color	Percentage of EDs (%)	Fast-Rate (GW1/GW2) (%)	Mid-Rate (GW1/GW2) (%)	Standard (GW1/GW2) (%)	Overlap (%)
1	Red	[60, 100]	**68.87/51.89**	11.43/15.24	0/0	**88.61**
2	Black	[45, 59]	31.13/48.11	40.95/27.62	8.49/9.43	11.39
3	Green	[30, 44]	0/0	**46.67/54.29**	33.02/28.3	0
4	Blue	[0, 29]	0/0	0.95/2.85	**58.49/62.26**	0



(a)

(b)

Figure 4.21: Percentage of successful transmissions (a) and average number of data packets successfully delivered by each ED (b) in the network zones with the RTS v2 protocol.

Rate EDs to transmit their packets, being able to access the medium more often than the EDs using slower rates, as shown in Figure 4.23a, and also due to their low transmission range which reduces the number of RTS packets received by them, as they only consider the RTS packets sent to them using Fast-Rate channel. The good quality of signal with their respective GWs increases the probability of the data packets to be successfully delivered, in case of collision, being the EDs that have the best performance relatively to percentage of successful transmissions, as shown in Figure 4.23b. Fast-Rate EDs are also the ones that, on average, listen to a lower percentage of network EDs which use the same ideal mode as them,

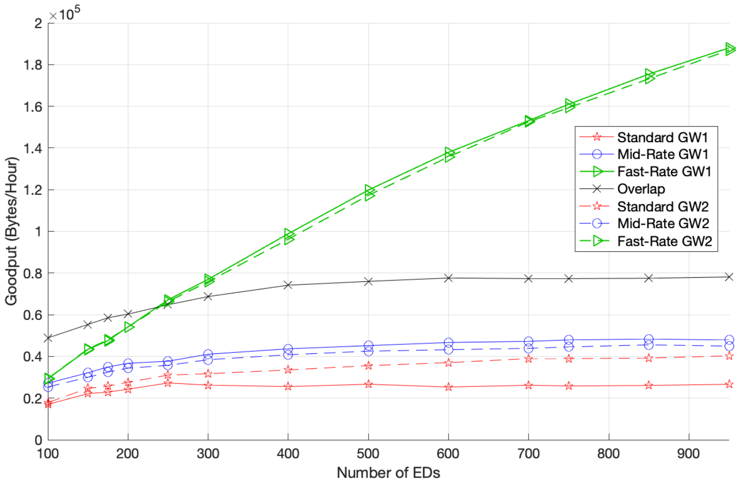
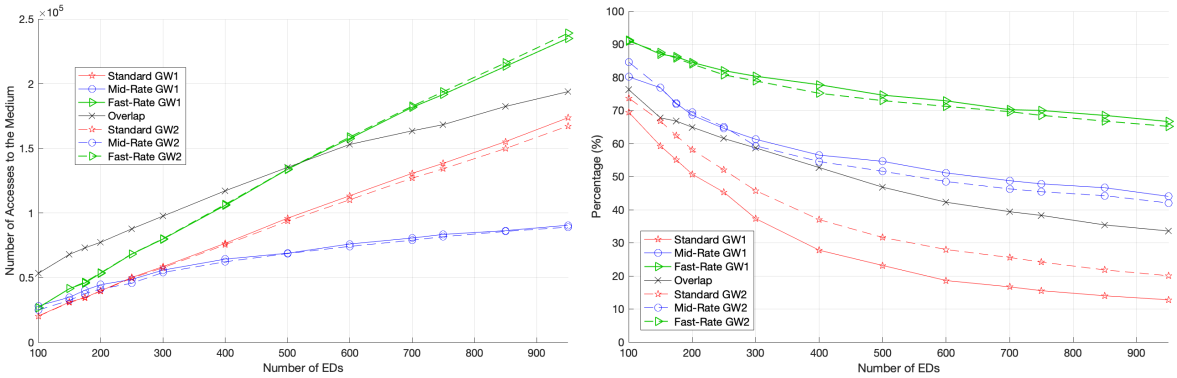


Figure 4.22: Aggregated goodput on each network zone with the CH-MICF protocol.



(a)

(b)

Figure 4.23: Number of medium accesses (a) and percentage of successful transmissions (b) in the network zones with the CH-MICF protocol.

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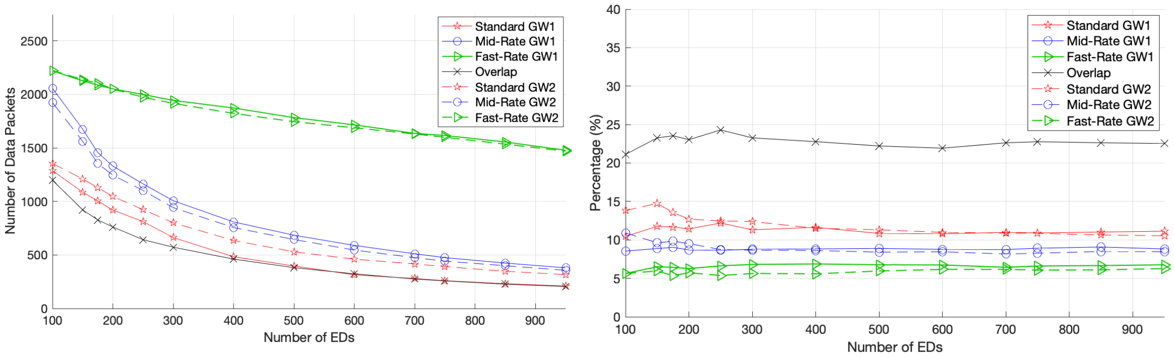
as Figure 4.24a shows, which contributes to their high number of channel accesses.

The second best goodput comes from the overlap zone as, similarly with the performance tests related to the RTS protocol, there are three times more EDs on this zone than in the other ones, which are only on reach of one. Actually, the overlap EDs are the ones which, alongside those from Standard zone, transmit successfully less data packets, as shown in Figure 4.24a. In this zone there are EDs that are able to send packets both in the Standard and Mid-Rate channel. Thus, the low number of packets per ED is not due exclusively to the lower transmission rate but also to the quantity of overheard RTS packets. In fact, they overhear a higher percentage of EDs than the EDs in the other network zones, as shown in Figure 4.24b. Figure 4.25 shows the distribution of the EDs according to the amount of EDs that are able to communicate with them, using the CH-MICF protocol. Table 4.8 contains the ED color legend and the percentages of each level of overhearing, per zone, based on the values contained in Figure 4.24b.

Regarding the Mid-Rate zone, as the EDs have a faster transmission rate and better quality of signal with the GW than the Standard ones, the goodput is better and have the



(a)

(b)

Figure 4.24: Average number of data packets transmitted successfully by each ED (a) and average percentage of EDs on the reach of each ED (b) for each network zone with the CH-MICF protocol.

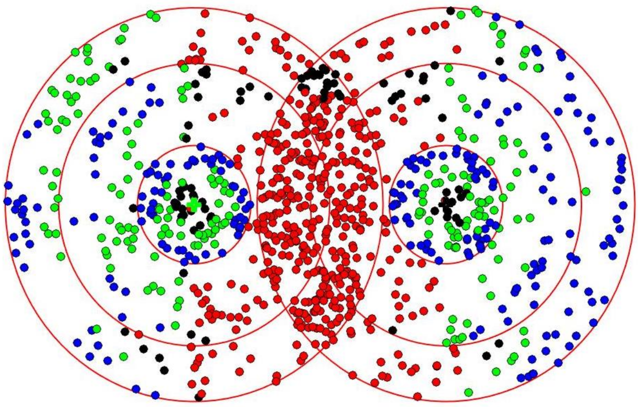


Figure 4.25: Network with 950 EDs colored according to the percentage of EDs that they overhear and using the CH-MICF protocol. The legend of each ED color, and respective range of percentages, is shown in Table 4.8, based on the results obtained in Figure 4.24b.

Table 4.8: Legend of Figure 4.25 regarding the color and percentage interval which corresponds to each level of overhearing. The percentage values in bold represent the maximum values for the respective network zone.

Level of Overhearing	**Color**	**Percentage of EDs (%)**	**Fast-Rate (GW1/GW2) (%)**	**Mid-Rate (GW1/GW2) (%)**	**Standard (GW1/GW2) (%)**	**Overlap (%)**
1	Red	[11, 100]	0.94/0.94	**33.33**/29.52	**37.74**/34.91	**94.3**
2	Black	[9, 10]	18.87/9.43	14.29/10.48	6.6/3.77	5.7
3	Green	[7, 8]	33.96/37.74	32.38/28.57	33.96/16.98	0
4	Blue	[0, 6]	**46.23/51.89**	20/**31.43**	21.7/**44.34**	0

second best percentage of successful transmissions, only behind the Fast-Rate zone, as shown in Figure 4.23b. Regarding accesses to the medium, Mid-Rate EDs have the shorter number, considering the zones reached only by one GW. This is caused by the lower time that these EDs have to transmit packets, in comparison with Standard EDs, despite they are able to transmit with a faster rate.

4.6 Final Remarks

This chapter focused on the Channel Hopping protocol, a new approach where the channel of operation of the EDs and GWs changes over time.

First, it was presented an introduction to the concept of ideal channel, the most suitable channel of operation for the EDs to transmit packets, based on the transmission quality between EDs and GWs. In the following, it was presented the detailed behavior of the EDs and GWs, individually, when using the Channel Hopping protocol, accompanied by the respective flow diagrams, so as to make the explanation clearer. The channel of operation of the three different versions of the new protocol were also shown through the use of different situations that helped to explain more clearly the behavior of the EDs. Next, was presented the simulation environment study and evaluation metrics used to obtain and conclude about the results obtained. At last, comparative study between the different versions of the Channel Hopping protocol and the RTS v2 was made, regarding the goodput and fairness of the network.

Chapter 5

Supplementary Evaluations

In the tests presented before, some parameters, as the overlap zone formed by both GWs and the number of GWs in the network, were never changed. Therefore, in this chapter we are going to evaluate the network performance when changing these and other parameters, check which are the most advantageous and disadvantageous locations within each network zone to transmit data packets and compare the studied protocols with a TDMA version of them.

Section 5.1 addresses a comparative study between adding an extra GW to the network and increasing of complexity of the protocol. Section 5.2 gives a closer look to the network EDs that achieve the best and worst performances within each network zone, for the RTS and Channel Hopping protocols, discussing the reasons behind each performance. Section 5.3 compares the network performance when the overlap area changes, concluding about the influence of the gateways' overlap area in the overall network performance. Section 5.4 addresses the performance of Channel Hopping protocol, namely CH-MICF, when varying the non-Standard channel times per cycle. Next, Section 5.5 compares the performance of RTS and Channel Hopping protocols with a TDMA version of each one of them, where each transmission is allocated to a specific time slot, coordinated by an omniscient controller, avoiding collisions. At last, Section 5.6 concludes the chapter.

5.1 Hardware vs. Protocol Complexity

In this section we test the performance of RTS and pure-ALOHA protocols adding an extra GW to the network, so to conclude about the payoff between adding hardware to the network and increasing the complexity of the used protocol, by the means of control packets and channel access coordination.

For this test was used the same simulation environment as in Chapter 3, however, in this case the number of EDs in the network varies between 100 and 2000 EDs and an extra GW was added to the network, as shown in Figure 5.1. Thus, two new network topologies were generated, each one with 2000 EDs, for the networks with two and three gateways, as the map used before only considers two gateways and 1000 EDs.

As shown in Figure 5.2, as an extra GW is added, the aggregated goodput of both protocols improved, being the increase in the pure-ALOHA protocol of about 95.22% and of 51.98% in the RTS protocol for 2000 EDs, the highest number of EDs tested. For a low density of EDs, and considering the same number of GWs, the pure-ALOHA is more advantageous

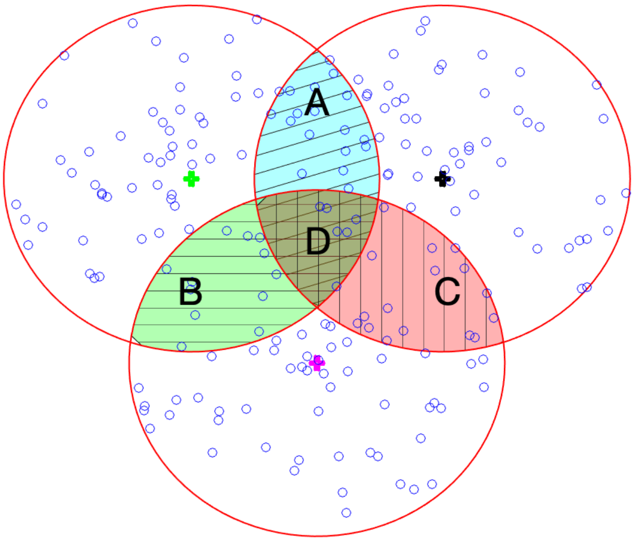


Figure 5.1: LoRa network with 3 gateways, GW1, GW2 and GW3, represented by green, black and magenta crosses, respectively, and 200 EDs, represented as blue circles. 'A', 'B', 'C' and 'D' mark overlapped coverage areas. When there are 3 GWs, all overlaps exist and EDs are equally distributed by their coverage area. For two GW networks, with only GW1 and GW2, EDs are equally distributed by their coverage areas and only overlap 'A' exists (but now encompassing 'D').

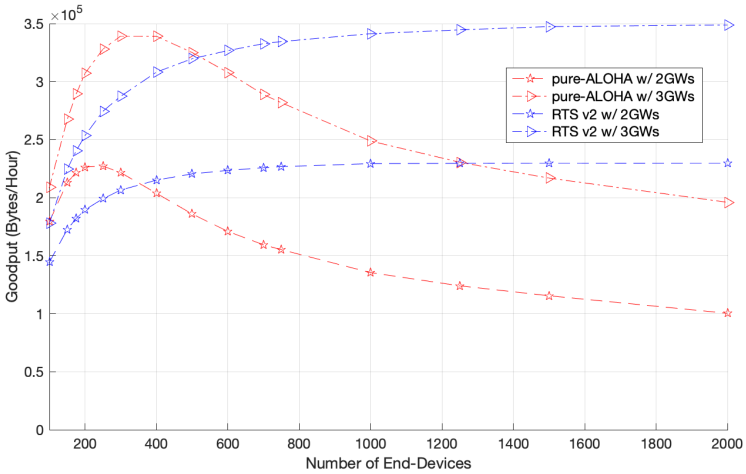


Figure 5.2: Goodput of the pure-ALOHA and RTS v2 protocols with 2 and 3 gateways for different network sizes.

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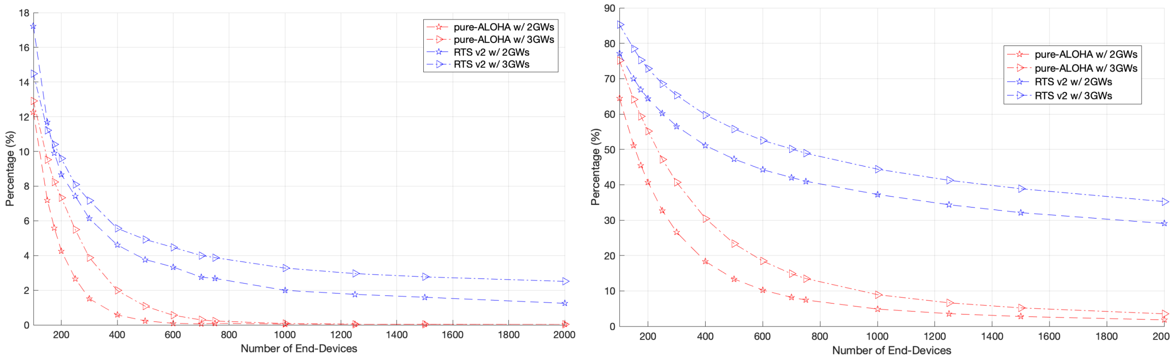
than RTS, as the EDs are able to access more often to the channel and so, despite the higher number of collisions, they can deliver a higher number of packets to the GWs. However, as the network grows, the goodput of RTS becomes better than the goodput of pure-ALOHA, which experiences a higher occurrence of collisions. The threshold number of EDs from which this happens increases with the increase in the number of GWs in the network, being of about 357 when there are 2 GWs and 522 when the network has 3 GWs. The network supports a greater number of EDs before it begins to get overloaded with transmissions that collide, causing loss of information that leads to a decrease in the aggregated network goodput.

Moreover, as the network scales even more, the RTS protocol outperforms pure-ALOHA's with one extra GW when the network has 1266 EDs. This is the threshold value from which is more advantageous to have a protocol with medium access control that reduces the number of packet collisions than a protocol with lower complexity, without any medium access control mechanism, and an extra GW. Therefore, for a number of EDs smaller than this threshold, the access control, which major goal is to assure a correct delivery of the packets, does not pay to be used, as the number of medium accesses is more reduced and not sufficient to overcome the medium access limitations of pure-ALOHA.

The percentage of duplicate packets among all packets received tends to zero, as the network scales up, for the pure-ALOHA protocol scenarios with two and three GWs, as Figure 5.3a illustrates. Despite that, for densities below 1000 EDs, this percentage is considerably higher for the scenario with three GWs, as the competition to access the medium decreases, as well as the number of collisions. In the RTS protocol, the percentage of duplicated packets also increased with the introduction of an extra GW, although now the increase is noticeable for all tested ED densities. This improvement is caused by the same reasons, regarding the reduction of the number of EDs competing to use the medium at the same time, which decreases the amount of collisions. Contrary to what happens in the pure-ALOHA protocol, in the RTS protocol this percentage does not tend to zero, as the network grows up to 2000 EDs, being of about 2.51% and 1.25% for the network scenarios with two and three GWs, respectively, for the higher density of EDs.

The delivery ratio also increased with the addition of a GW in both protocols, as shown in Figure 5.3b, being the highest growth recorded in the RTS protocol, from 29.06% to 35.24%, when the network has 2000 EDs. In the pure-ALOHA the increase was smaller, from 1.8% to 3.52%, for the same density of EDs. However, as there are more collisions in the pure-ALOHA protocol, the improvement is greater for networks with a lower density of EDs, decreasing as the network grows.

From this, we conclude that, when introducing an extra GW, the percentage of duplicated packets and delivered transmissions increase in both pure-ALOHA and RTS protocols and for a network with less than 1266 EDs the insertion of an extra GW to the network, already



(a) (b)

Figure 5.3: Percentage of duplicated packets (a) and percentage of successful transmissions (b) of the pure-ALOHA and RTS v2 protocols with 2 and 3 gateways for different network sizes.

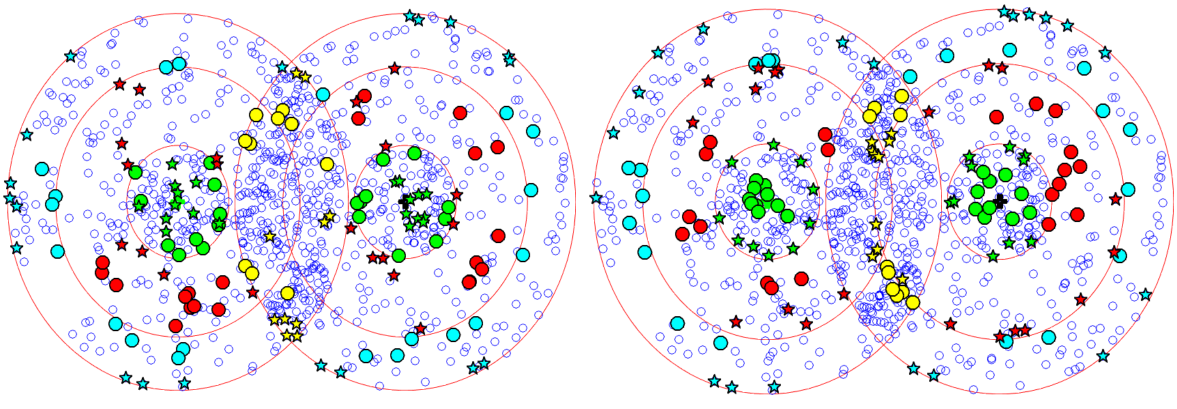
using two gateways, and maintaining a low complexity protocol, achieves a better goodput than increasing the complexity of the medium access protocol. However, as the 1266 EDs threshold is surpassed, the use of an extra gateway is no longer the best option to achieve the best network goodput, being more advantageous to increase the complexity of the transmission protocol.

5.2 Reference EDs Performance

Section 4.5.4 presented the performance of each network zone, individually, for both protocols. Now we will study the performance of the EDs within each network zone for the RTS v2 and CH-MICF protocols, in order to conclude about the locations within each zone where the EDs achieve the best and worst performances. In Figures 5.4a and 5.4b are depicted the EDs that achieve the ten best and ten worst goodputs in each network zone, when using the RTS and the Channel Hopping protocols, respectively. The circles represent the best performing EDs in each zone, whilst the stars are the EDs which achieved the worst performances.

5.2.1 Standard Zone

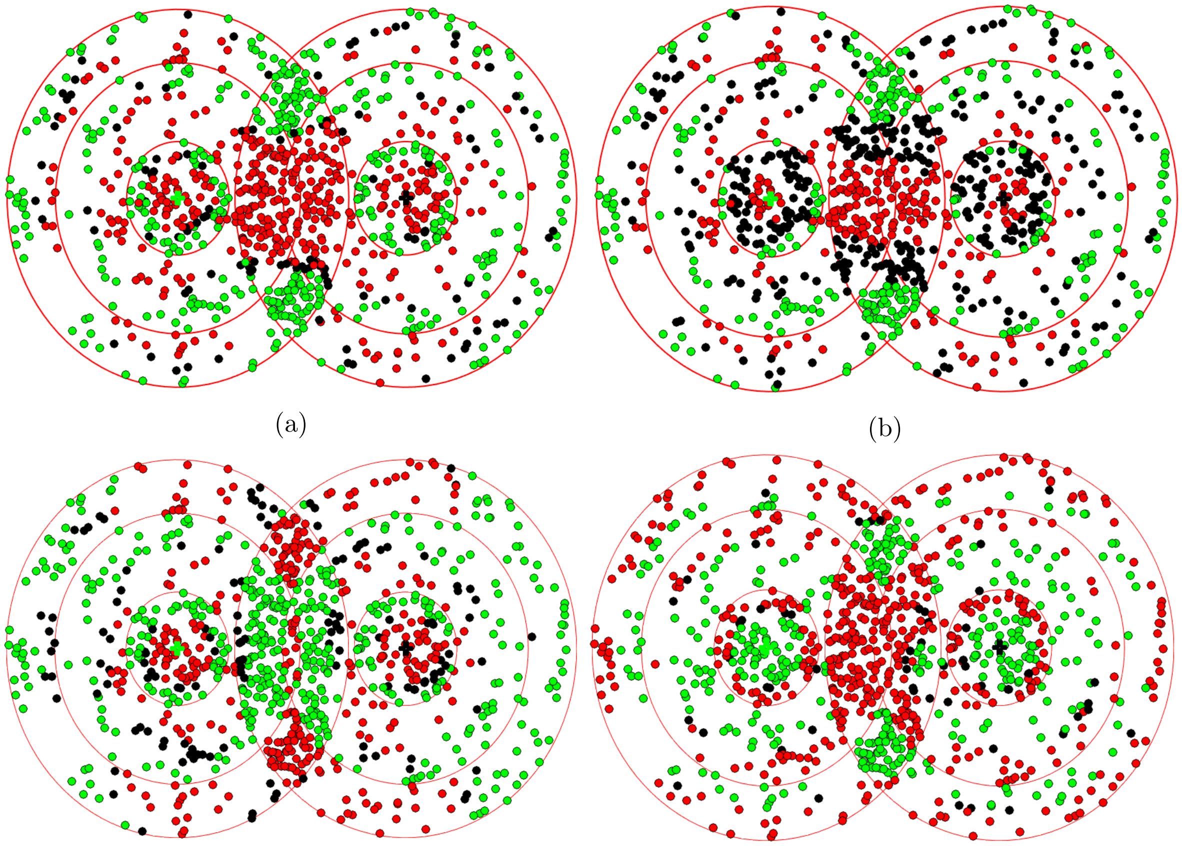
In the Standard zone, the EDs with the best goodput in both protocols are those that are located closer to the border with the Mid-Rate zone as, despite receiving a higher number of RTS packets (Figures 5.5b and 5.5c), mirrored in the lower number of accesses, they are more likely to successfully transmit their packets, as they have a better signal quality with the GW. The EDs with worse goodput are located on the edge of the gateways' reach. As they overhear a small number of RTS packets, are able to access the medium more often but, as their signal quality is worst, their likelihood to transmit successfully is lower.



(a)

(b)

Figure 5.4: Network with 950 EDs and two GWs with the ten best and worst performing EDs of each network zone, for the RTS protocol (a) and the Channel Hopping protocol (b), depicted as a circle and a star, respectively. Standard selected EDs are represented in cyan, Mid-Rate and Fast-Rate ones in red and green, and overlap ones are represented in yellow.



(a)

(b)

(c)

(d)

Figure 5.5: Number of medium accesses for the RTS protocol (a), number of received RTS packets for both RTS (b) and Channel Hopping (c) and the percentage of successful packet transmissions by each ED relatively to the mean value of the network zone for the Channel Hopping protocol (d). For (a) the color green represent the EDs that are able to access the medium more often, 5% more than the average value of the respective zone, the black EDs are able to access the medium more than 95% of the average value and for less than that, the EDs are represented in red. For (b) and (c) the red color represents the EDs that overhear more RTS packets, 5% more than the average value of the respective zone, and the black EDs receive more than 95% of the average value. For (d) the green color represents the EDs that have a higher percentage of successfully transmitted packets, 5% more than the average percentage of the respective zone, the black EDs are able to transmit successfully more than 95% of the average percentage and, for less than that, the EDs are represented in red.

5.2.2 Mid-Rate Zone

For the RTS protocol, the worst performing EDs in the Mid-Rate zone are mainly located closer to the border with the Fast-Rate zone. These overhear a high number of RTS packets, as shown in Figure 5.5b, as they are closer to the GW, that prevents them from transmitting as often as the EDs located closer to the border with the Standard zone, which receive a lower number of RTS packets, accessing the channel more often, as shown in Figure 5.5a. Due to the lower number of overheard control packets, some collisions occur but, as long as their signal quality is better than the ones in the Standard zone, their likelihood of a successful transmission is higher.

For the Channel Hopping protocol, the EDs closer to the border with the Standard zone, despite accessing more often, achieve the worst performance. This is due to the lower competition to access the medium, relatively to the RTS protocol, enabling the EDs closer to the Fast-Rate zone border to transmit more, as they have better communication quality with the GW and the amount of overheard RTS packets, despite being higher, does not prevent them from transmitting for too long, as occurred in the RTS protocol. As Figure 5.5d shows, the percentage of successful transmissions is related with the distance between the EDs and their respective gateway, as this percentage increases when the distance to the gateway decreases, and vice-versa.

5.2.3 Fast-Rate Zone

In the Fast-Rate zone, as in the Mid-Rate zone, the best and worst performing EDs for both protocols are in opposite locations. For the RTS protocol, as the competition to access the medium is higher, the further the EDs are from the GW, the better their performance, as the EDs overhear a smaller amount of RTS packets and thus, access the channel more often. Regarding the Channel Hopping protocol, as the only EDs competing for the medium are the ones located in the same zone, there is less competition. Thus, despite the greater number of RTS packets, the EDs closer to the GW achieve the best performance, due to their quality of signal.

5.2.4 Overlap Zone

For the RTS protocol, the overlap EDs that achieved the best performance are in two distinct locations. One is in the Standard zone of both GWs, closer to the border with the Mid-Rate zone, as the EDs transmit more often, as shown in Figure 5.5a, and, as they are the ones that are closer to the GW in the Standard zone of both GWs, are very likely to transmit successfully. The other location is in the Standard zone of a single GW, closer to the edge. This is the closest that an overlap ED can be to a GW, and thus with better signal quality, and that is reflected in the performance. Regarding the worst performance for the RTS protocol, most of the EDs are located in the Standard zone of both GWs, close to the edge and so, with a bad quality of communication with both GWs.

For the Channel Hopping protocol, as the EDs only transmit with the fastest channel, the best performing ones are located in the Standard zone of both GWs, closer to the border with Mid-Rate, as the quality of signal is better and they are able to transmit to both GWs. The EDs in the Mid-Rate zone of both GWs do not achieve the best performance, despite the rate of transmission is faster, as the zone is very narrow and the EDs placed there have a bad quality of communication. The worst performing EDs are located in the Mid-Rate zone of a single GW, closer to the border with the Standard zone. There, the EDs, in addition of being able to transmit just to a single GW, also have the worst signal quality among those that use the same channel.

5.3 Overlap Influence

To assess the influence of the overlap region formed by the two GWs in the network performance using the RTS and Channel Hopping protocols, two different overlaps than the one used in the previous tests (Figure 5.6b) were created, one with a smaller area (denoted as Overlap 1 and illustrated in Figure 5.6a), pushing the GWs away from each other, and another one with a greater area (denoted as Overlap 3 and illustrated in Figure 5.6c), bringing the GWs together.

5.3.1 Goodput Analysis

Figure 5.7 illustrates the network goodput for the different overlaps achieved by the RTS and the Channel Hopping protocols. As shown, although the network goodput obtained by the RTS protocol with the different overlaps is very similar, the same does not occur with CH-MICF, where a higher goodput is achieved with Overlap 3, a behavior even more evident as the network grows. This is due to the approach of the GWs that allows EDs in the overlap zone whose ideal channel is Mid-Rate relatively to both GWs to have better signal quality when transmitting data packets. Therefore, as these EDs transmit faster than the ones in the Standard zones and are able to send whenever each one of the GWs is using its ideal channel, they are able to transmit more often and with a higher Delivery Ratio, as shown in Figure 5.8a.

As the network Delivery Ratio, that increased with Overlap 3, as the overlap area is bigger than in the other two, the percentage of data packets received by, at least, one GW,

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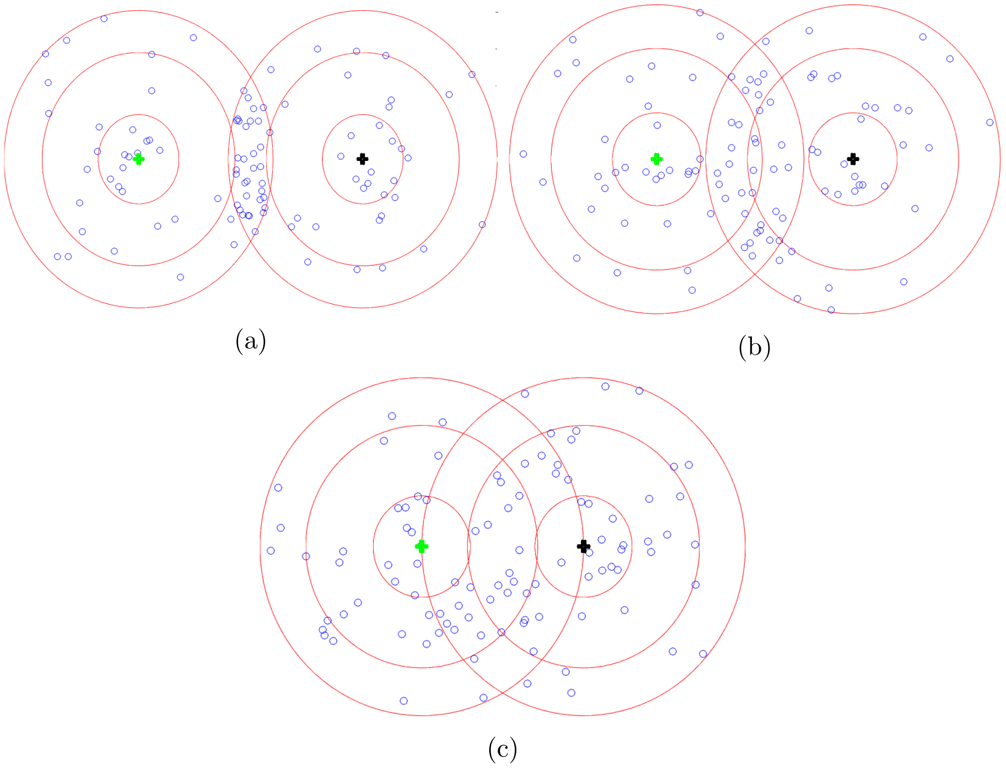

(a)

(b)

(c)

Figure 5.6: Network with 100 EDs and Overlaps 1 (a), 2 (b) and 3 (c).

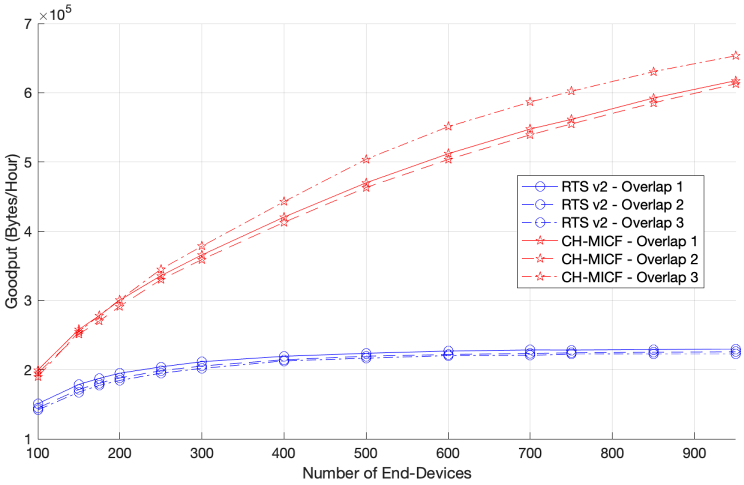
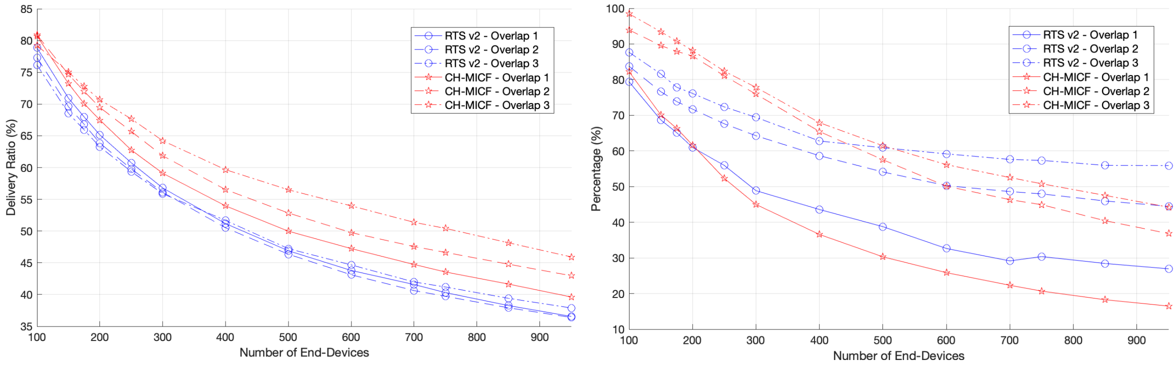


Figure 5.7: Network goodput for three different overlaps with RTS v2 and CH-MICF protocols for different network sizes.



(a)

(b)

Figure 5.8: Network delivery ratio (a) and percentage of data packets decoded by, at least, one GW but that could be decoded by both of them (b) for the three different overlaps with RTS v2 and the CH-MICF protocols for different network sizes.

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but that could be received by both of them, increased as well with the overlap area, as shown in Figure 5.8b. The network topology with the smallest overlap area, Overlap 1, on the other hand, presents the lowest percentage of successfully delivered packets that could be duplicated and were received by both or just one of the GWs. As the network scales, the difference tends to increase in the protocol CH-MICF and for 950 EDs the difference is around 11% relatively to the Overlap 2 and, approximately, 30% when compared with Overlap 1. The overlap area is one of the parameters that influenced the overall network goodput, that increases with the increase of the overlap area. However, with the increase of the overlap area, the overall network area decreases.

Another parameter that influences the variation of the network goodput, with the overlap area manipulation, was the amount of packet collisions. As the GWs become closer, the RTS packets sent by the EDs are capable of reaching a higher number of neighbors and thus, the percentage of collisions decreased with the increase of the overlap area, as shown by

Figure 5.9a. The percentage of received packets even experiencing collisions also increased with the increase of the overlap area, as shown in Figure 5.9b.

5.3.2 Fairness Analysis

Regarding the network fairness, shown in Figure 5.10, Overlap 3 presents the best results for both protocols, as the network scales, being the differences between the three overlaps in the RTS protocol more significant than in the CH-MICF, where, besides Overlap 3 (that stands out), Overlap 1 and Overlap 2 present very similar values. This is due to the approximation of the GWs, that decreases the total coverage of the network; the EDs are closer to each other and so, each one is able to overhear a higher number of RTS packets, reducing the amount of collisions. Such reduction in the number of collisions decreases the number of situations where the packets are decoded successfully by the GWs based on their signal quality, increasing the network fairness as a packet with bad signal quality is as likely to be

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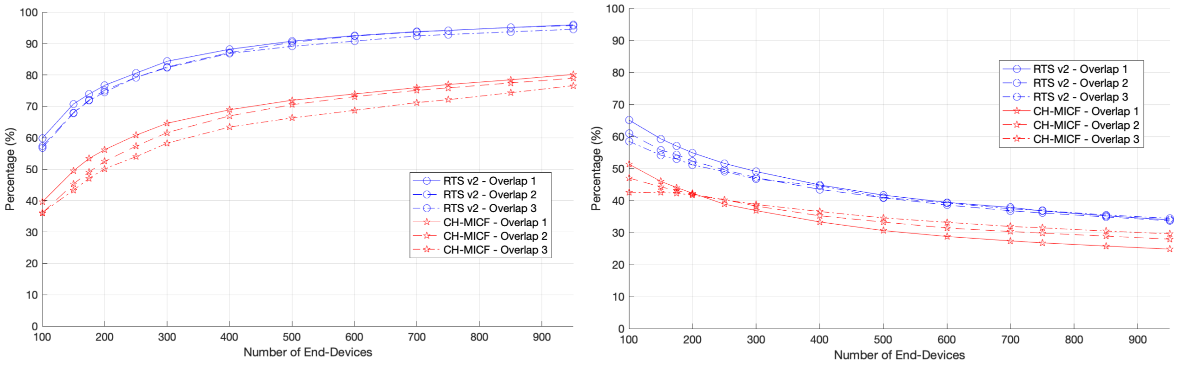


(a)

(b)

Figure 5.9: Percentage of collisions, considering all the medium accesses (a), and the percentage of successful transmissions from those which collided (b), with RTS v2 and CH-MICF protocols for different network sizes.

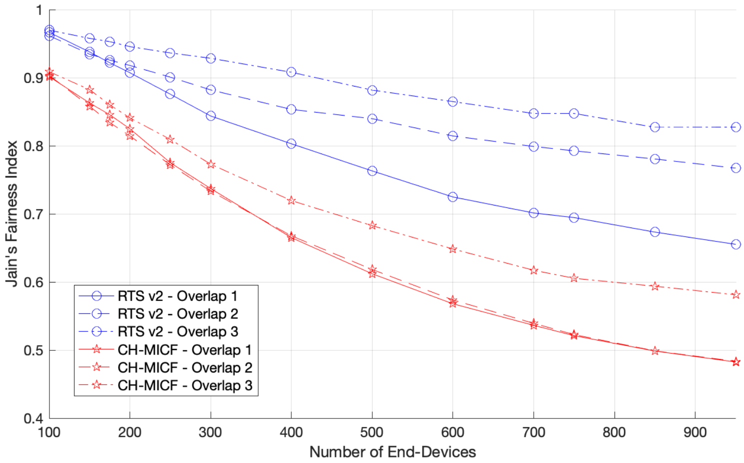


Figure 5.10: Network fairness for the three different overlaps with RTS v2 and CH-MICF protocols for different network sizes.

correctly decoded by the GWs as a packet with a better signal quality.

5.4 GW Channel Time Variation

In the Channel Hopping protocols tested before, the GW periods in each non-Standard channel remained the same, with 10 seconds for the Mid-Rate and 7.5 seconds for the Fast-Rate channel, per cycle. With the manipulation of these times, the behavior of the network goodput and fairness can be deeply changed, because different channels have different rates and transmission reaches.

Therefore, some tests were performed in this scope, in order to observe the influence that the time variation in each non-Standard channel has in the network goodput and fairness, using the overlap referred as Overlap 2 in Section 5.3 (Figure 5.6b).

5.4.1 Goodput Analysis

As shown in Figure 5.11, Fast-Rate time given to the GWs is the one that most influences the network goodput, since its increase by 2.5 seconds is more noticeable than when the same increment is made in the Mid-Rate channel time. This occurs as the Fast-Rate EDs transmit their packets faster than the EDs in the other network zones and thus, the mandatory backoff time that they have to respect after every transmission is also smaller. Therefore, they not only transmit more packets in the same time interval than the EDs in the other network zones, but also the backoff after every transmission, in order to respect the duty-cycle restriction, is also smaller. So, the network goodput has a faster increase, as the network grows, for the cases when the Fast-Rate channel time is equal to 7.5 seconds (red curves), followed by the case when Fast-Rate channel time is 5 seconds (blue curves). The worst case is when Fast-Rate channel time is equal to 2.5 seconds (black curves), where the goodput values, as the network scales up, slowly increase, due to the short time allocated to the Fast-Rate EDs, the ones that influence more actively the network goodput.

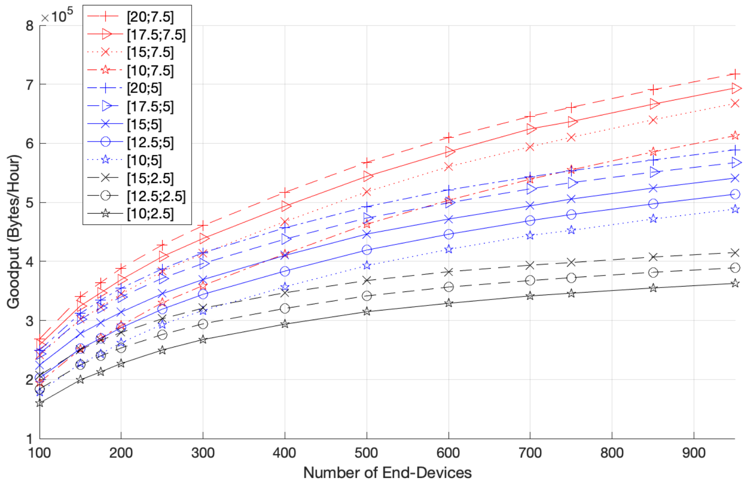


Figure 5.11: Network goodput with the CH-MICF protocol for different non-Standard channel times, per cycle. Each time combination is represented as [X;Y], being X and Y the Mid-Rate and Fast-Rate channel times, respectively, in seconds, per cycle.

Table 5.1: Goodput and Jain's Fairness Index values for each non-Standard channel time combination in a network with 950 EDs.

[Mid-Rate;Fast-Rate] (seconds)	**Goodput (Bytes/Hour)**	**JFI**
[20; 7.5]	**717500**	0.5592
[17.5; 7.5]	693600	0.5506
[15; 7.5]	667500	0.5343
[10; 7.5]	612800	**0.4834**
[20; 5]	589000	0.6594
[17.5; 5]	567200	0.6730
[15; 5]	541100	0.6693
[12.5; 5]	513800	0.6544
[10; 5]	488600	0.6237
[15; 2.5]	415000	0.7596
[12.5; 2.5]	389100	**0.7810**
[10; 2.5]	**362700**	0.7712

According to the goodput values when the network has 950 EDs, shown in Table 5.1, increasing the Fast-Rate channel time by 2.5 seconds allows the GWs to receive more 1260 data packets per hour, on average, whilst by increasing the Mid-Rate channel time by 2.5 seconds the increase is of about 255 data packets per hour. Thus, the increase in the number of packets, per increment of 2.5 seconds in the channel time, is about five times higher in the Fast-Rate channel. Therefore, as shown in Figure 5.11, as the network scales up, the combination [10;7.5] outperforms the combination [20;5], despite the time allocated for non-Standard channels being lower.

5.4.2 Fairness Analysis

Regarding the network fairness, despite what happens in the goodput, the higher the time allocated to Fast-Rate channel, the lower the fairness, as the network scales up, as noticeable in Figure 5.12. This occurs because EDs using this channel are able to send packets faster and back off less time after every transmission than the ones using slower channels. On the contrary, with the increase of the Mid-Rate channel time the fairness of the network does not always decrease, as seen in Figure 5.12. For 950 EDs, when the Fast-Rate channel time is 7.5 seconds (red curves), the combination with the best fairness is the one with the highest Mid-Rate channel time tested. This happens because, as the Mid-Rate EDs have more time to transmit, the difference in the number of packets transmitted when compared with the Fast-Rate EDs decreases, therefore improving the network fairness. However, the higher the Mid-Rate channel time does not mean an increase in the network fairness as the gap in the number of transmitted packets between the EDs of the faster channels, Mid-Rate and Fast-Rate EDs, and the ones using the slower channel, Standard EDs, will rise, degrading the fairness. This is shown in Figure 5.12, when the network has 950 EDs, for the combinations [...;2.5] (black curves), where the best combination has 12.5 seconds of Mid-Rate channel time and not 15 seconds, which in fact achieves the worst value of fairness.

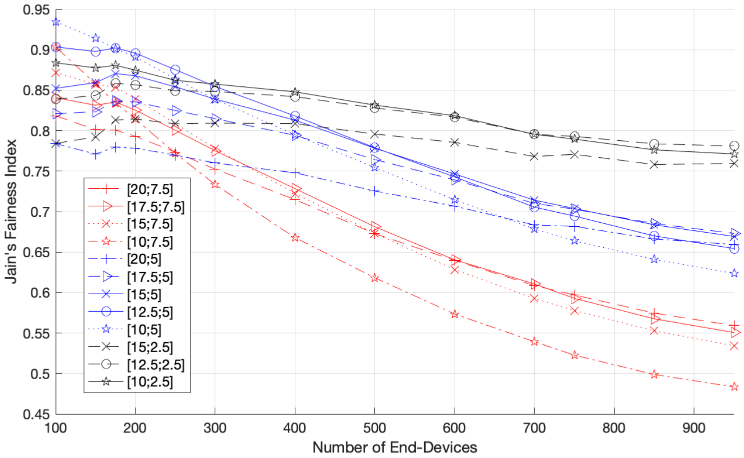


Figure 5.12: Network Fairness with the CH-MICF protocol for different Times in the non-Standard channels, per cycle. Each time combination is represented as [X;Y], being X and Y the Mid-Rate and Fast-Rate channel times, respectively, in seconds, per cycle.

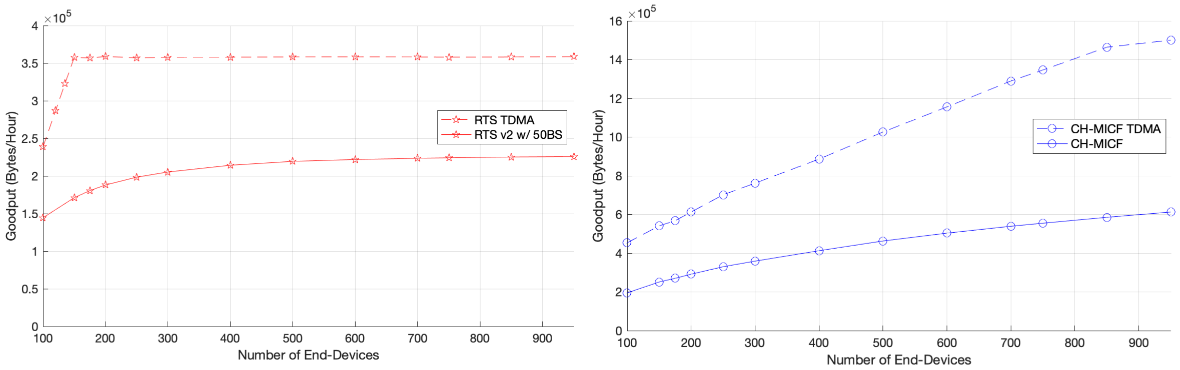
5.5 TDMA Comparison

In order to check how far the performance of the protocols proposed in this dissertation are from the ideal case, were developed MATLAB simulators of TDMA versions of the RTS and Channel Hopping protocols, where each transmission is properly allocated and there are no collisions. This ideal protocol was tested using Overlap 2, presented in Section 5.3 and the Mid-Rate and Fast-Rate channel times of 10 and 7.5 seconds, respectively.

In the TDMA version of the RTS protocol, the EDs able to communicate with a single GW are the ones that transmit first. As they are able to reach only one of the GWs, two simultaneous transmissions made by EDs that reach different GWs do not interfere with each other and so, two EDs transmit packets at the same time. After all EDs on the exclusive reach of a single GW transmit a data packet, the overlap EDs start to transmit their packets. In this case, as the EDs are able to communicate with both GWs, in order to avoid collisions, only an ED transmits at a time, which is received by both GWs. As soon as all overlap EDs have transmitted, the EDs on the reach of a single GW start to send their packets again and so on.

As shown in Figure 5.13a, for the network with 950 EDs, the goodput of the TDMA version of the RTS protocol is 59.8% better than the RTS v2 with 50 BS. The saturation of the TDMA version of the RTS protocol occurs when the network has 150 EDs, as from this point onwards there are enough EDs in the network to have, at least, one of them transmitting. For less than 150 EDs, the waiting time that the EDs take after a transmission, in order to comply with the duty-cycle restriction, is bigger than the time that the other EDs take to transmit their packets. Thus, there are time intervals that are not used to transmit packets. With 150 EDs on then network, it takes the time correspondent to 100 transmissions to every ED transmit a data packet, as each network zone has 50 EDs and the zones only within reach of one of the GWs send packets simultaneously. Thus, as soon as the last one finishes sending it, the first one is ready again, without needing to wait any longer in order to fulfill the duty-cycle restriction.

In the TDMA version of the Channel Hopping protocol, each ED, similarly to the TDMA



(a)

(b)

Figure 5.13: Goodput of RTS v2 (a) and CH-MICF (b) with their respective TDMA version.

of the RTS protocol, transmit sequentially, according to a predetermined order, so that every ED has the same opportunity to transmit.

As shown in Figure 5.13b, the goodput of the TDMA version of the Channel Hopping protocol outperformed the CH-MICF protocol network goodput, for the same non-Standard channel times. For 950 EDs, the maximum density of EDs in the network tested, the performance of the TDMA version is 145% better than the one achieved on the CH-MICF, as the transmissions are scheduled, avoiding collisions, allowing the EDs on the different network zones to transmit a higher number of packets.

5.6 Final Remarks

This chapter focused in a more detailed evaluation of the RTS and Channel Hopping protocols, varying parameters that remained constant in the previous chapters, studying EDs individually and comparing each protocol's performances with an ideal one, where the transmissions are scheduled to occur as fast as possible and without any collision.

First, it was presented a comparative study between the addition of more hardware to the LoRa network, namely an extra gateway, and the changing from a medium access protocol with low complexity to a more complex one, in order to understand when one would be more advantageous than the other. For a high quantity of EDs in the network the most suitable solution is to increase the complexity of the medium access protocol, whilst when the density is low, adding an extra gateway is more advantageous with respect to the network goodput. In the following, the EDs that achieved the best and worst goodput within each network zone were analyzed, concluding about the best and worst locations. Next, the overlap zones were manipulated, approaching and moving away the network gateways from each other, concluding that when the gateways are closer, the network goodput is better as there are less collisions because each ED is able to overhear a higher number of RTS packets sent by the other EDs. Next, the non-Standard channel times per cycle were changed when using the Channel Hopping protocol, in order to conclude about the influence of these in the network overall performance. It was concluded that, as the Fast-Rate channel time increases, the network goodput increases as well but the network fairness decreases, as the EDs on the Fast-Rate zone are able to transmit a higher quantity of data packets than the EDs on the other network zones, as they are able to transmit faster than the others. At last, the performance of the RTS and Channel Hopping protocols were compared with their respective TDMA versions, where every transmission is scheduled and there are no packet collisions.

Chapter 6

Conclusions and Future Work

This dissertation focused mainly on studying different MAC strategies for LoRa networks, one of the most fitable technologies for IoT applications, due to its inherent characteristics such as long-range communications, enabled by its proprietary modulation scheme that allows transmissions below the noise level, simple deployment and low maintenance and setup costs.

Initially, as a basis of the study, a pure-ALOHA based strategy like LoRaWAN, the most used one in LoRa networks, was tested in large-scale networks with two single-channel GWs. With this access strategy, the EDs were able to transmit whenever they want, as long as they complied with the duty-cycle restriction. As expected, and noticeable, as the network scaled up, the network goodput degraded because of the increase in the number of collisions. Such increase also led to a decrease in the network fairness, as the EDs with a better signal quality with the GWs were more likely to transmit successfully, increasing the performance difference between EDs.

In order to get around these drawbacks, an alternative strategy was proposed; the RTS protocol. This was based on the pure-ALOHA based strategy, to which control packets have been added and the EDs had also the ability to filter control packets, discarding those adverting transmissions that could only be received by a GW that is not in its reach. This feature improved the network performance, while giving a reasonable amount of transmission opportunities to the EDs with more overheard neighbors, such as the ones closer to overlap zones. So, these new features improved both the network goodput and fairness, providing more similar opportunities for all EDs to transmit and preventing transmissions from being lost due to collisions.

Despite the improvements brought by the RTS protocol, the transmissions were not adapted according to the location of each ED, using the same transmission parameters for all EDs. In fact, in order to allow all of them to transmit, from those which are closer to the GW to those at the edge of the network, the transmissions were adapted only for those which were further from the GW, causing many other transmissions to take longer and spending more power than would be necessary.

In order to overcome this problem, a new protocol named Channel Hopping was proposed. In this, the transmission parameters of the network devices are no longer static, as they were before, changing according to the network profile. Thus, the network was subdivided into three new zones, in relation to each GW, where EDs have similar signal quality characteristics. For each ED to be able to transmit in its so-called ideal channel, it needs that, at least, one GW in its reach is also using it. Thus, the GWs need to change their channel characteristics over time, in order to give opportunity to all network zones, assigning time intervals to each one. The strategy with channel hopping that achieved the best performance, namely CH-MICF, increased the communication efficiency, improving the network goodput, due to the transmission characteristics being more appropriate to the network scenario, allowing for faster data exchanges, when possible.

In the following, a study was carried out on the performance of each network zone, for both RTS and Channel Hopping protocols. With the RTS protocol, as the competition to use the medium was higher than in the Channel Hopping protocol, the quantity of received RTS packets by each ED was higher and, as the network grows, undermined the performance of the zones where the EDs overhear a greater amount of control packets, namely the Fast-Rate zone ones, due to their proximity to the GW. These, running out of many opportunities to transmit, saw their performance drop, despite the success in transmission remaining high due to their good communication link with the GW. The zone in which the performance was most favored was in the Mid-Rate, where the EDs do not overhear as many RTS packets as the Fast-Rate ones and have a better communication link with the GW than the Standard ones, being more likely to deliver packets than these. Relatively to the Channel Hopping, as each network zone transmits using different channels, the quantity of RTS packets received by the EDs is reduced and there is less competition to access the medium. For this reason, the Fast-Rate EDs, as they transmit faster, are the ones that achieved the best aggregated goodput, as well as the highest percentage of successfully delivered packets.

At last, a supplementary evaluation of two MAC protocols took place, varying network parameters, such as the overlapping of the GWs' coverage areas and the time dedicated to each channel, that had previously remained unchanged.

It started by studying the trade-off regarding the use of an extra GW and a more complex medium access protocol, considering the evolution from the pure-ALOHA to the RTS protocol. From this study it was concluded that the increase in the number of GWs, below a certain network size, is justified, since the number of EDs competing for the medium is reduced, as there is one more GW. However, for larger networks, the performance of RTS becomes better than the pure-ALOHA's with an extra GW.

Next, EDs were analyzed individually, according to their performance, with the best and worst within each zone being identified, for both protocols. For the RTS protocol, despite the Standard EDs, those that performed better within the other two zones that are on the reach of a single GW were those that were furthest from the GW, as they overhear the least amount of control packets, hence they have a greatest opportunity to transmit. The same did not occur in the Standard zone because the EDs are not as influenced by the control packets and the closer they are to the GW, the more chances they have to transmit successfully. Regarding the Channel Hopping protocol, it was unanimous that the EDs with the best performance were those that, within each zone, are closest to the GW.

After this, the overlap zone was manipulated, increasing and reducing it compared to that used up to that point. Whilst the goodput and delivery rate results obtained with the RTS protocol was very similar to all tested overlaps, as all EDs use a unique, static channel, with the Channel Hopping protocol a network with the largest overlap area was noticeable better.

In the following, the channel periods have been changed and, as expected, the time allocated to the Fast-Rate channel is the one that most profoundly influences the network performance, regarding both goodput and fairness. This is so as the EDs that use this channels are able to transmit faster, hence, the longer they are capable of transmitting, the greater the difference in packets transmitted between them and the other EDs that use the slower channels, decreasing the network fairness. The goodput, in turn, improves due to the greater number of transmissions made by the Fast-Rate EDs.

Finally, it was studied the difference between the RTS and Channel Hopping protocols and their respective TDMA (and hypothetical) versions was studied. From this was concluded that both protocols are still far from what would be their ideal performances, needing improvements. Thus, the best performing Channel Hopping protocol developed in this dissertation, CH-MICF, is yet far from ideal, requiring adjustments in order to get closer to it.

The following topics briefly describe a few research lines that can be followed, in order to increase the performance levels of the protocols developed and validate its use in real-life networks:

- Adapt the maximum number of backoff slots according to the number of EDs in the network and with the regularity that they transmit packets, in order to increase the efficiency. The latter refers to allocating a longer average backoff time to EDs capable to transmit more often so to give more opportunities to those who spend some time without transmitting, improving the network fairness;

- Introduce mobility to the network in order to obtain a performance closer to that which would be obtained in a scenario where the sensors move around within the coverage of the network;

- Use adaptive channel periods, instead of fixed ones, according to the distribution of ED by the different network zones, considering that the devices have mobility and are able to change from a zone to another.

- Further validation of the studied access strategies, testing them in a real-life scenario and comparing the performance results with the ones obtained through simulation, concluding about the applicability of the develop protocol in a real-life network.

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