


# Scalability in LoRaWAN

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Challenge the future

# Scalability in LoRaWAN

by

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in partial fulfillment of the requirements for the degree of

**Master of Science**
in Embedded Systems

at the Delft University of Technology,
to be defended publicly on Tuesday November 20, 2018 at 10:00 AM.

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

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# Acknowledgements

First and foremost, I would like to extend my deepest gratitude to my supervisor Dr. R.R. Venkatesha Prasad for his continuous support during the period of this master thesis. For his patience, motivation, and immense knowledge. His guidance helped greatly me during the time of research and writing of this thesis.

I would also like to extend my sincere thanks to Dr. Ir. V. Rao. His guidance and support have been instrumental in driving this work. In times of confusion his sound advice gave clarity to my thoughts. His extensive knowledge has broadened my intellectual horizon and challenged me. I am also thankful to Ir. N. Kouvelas. His patience, dedication and friendly nature have helped me cross many hurdles throughout this process. Whenever, I've needed a helping hand, I've found it in him.

This thesis is a culmination of all my studies as a TU Delft student. The journey so far has been brutal but rewarding. It is a unique experience in so far as being the first time I have lived away from home. There have multiple times when I've stumbled, lost my courage, but it is these moments that have brought me closer to my loved ones. The unwavering belief that my parents have in me has instilled in me the courage to conquer every obstacle I've faced. No matter the distance or time, they have always been only a phone call away. My mother Swati, has been my rock. She has been my strength when I was weak, a stern mother when I wavered, a confidant when I needed one. But above all, she has inspired me. Her work ethic and relentless hard work encouraged me to strive to be like her. The next person who is my rock is my father Shekhar. He has always believed in me, always stood by my decisions and been an unconditional support in my life. He hasn't doubted me or my abilities even when I did, and pushed me to achieve all my goals.

At this point I can't help but think of my grandmother. I am who I am today because of her. She taught to draw when I was young and cope with the ways of the world as I grew older. She raised me to be face every hurdle with confidence and determination. If she was here today, I hope she'd be proud of the person I've become.

Finally, I would like to thank all my friends and family. The many friends, old and new, who have encouraged me, laughed and stood by me. A special thank you to Geert, Maria and Sjef for extending their home and family so I never feel alone. Their unconditional love and support has gone a long way in making this journey a beautiful experience.

*Gauri Chandrashekhar Tawde*
*Delft, November 2018*

# Abstract

The concept of a network of smart devices has been discussed in seminars and conferences by researchers as early as the 1980s as the technology which would allow computers, rather than people, to manage individual things. Since then however, there have been substantial technological advancements in this field. Smarter cities and industries has given rise to a need for large-scale sensor monitoring networks. This rise in connected devices has placed emphasis on the development of low power wireless communication technologies with long ranges, often referred to as Low-Power Wide Area Network (LPWAN). These technologies are intended to connect low cost, low power and low bandwidth devices. LoRaWAN is one such inexpensive and energy efficient LPWAN. It is a star topology network following ALOHA transmission protocol. It operates in the unlicensed ISM bands and is subject to regulatory constraints.

This work is a study into the channel throughput produced by a single channel LoRaWAN gateway under various traffic load conditions. In heavy traffic conditions the ALOHA protocol starts to fail. As a solution, the use of Carrier Sense Multiple Access (CSMA) protocols has been proposed. Three network scenarios - Centralized, Distributed and Hybrid were envisioned in which persistent Carrier Sense Multiple Access (p-CSMA) and non-persistent Carrier Sense Multiple Access (np-CSMA) techniques were applied. Event-driven simulations were developed to analyze and compare their throughput and energy results. Hybrid np-CSMA produced the highest throughput and the most energy efficient network.

As LoRaWAN does not inherently possess carrier sensing, the Carrier Activity Detection (CAD) mode in LoRa was studied and applied. Extensive experiments were carried out to test the accuracy and sensing range of devices for each datarate.

This study provides insights into the implementation of unslotted carrier sensing techniques in LoRaWAN. It was concluded that, while the ALOHA like LoRaWAN can perform effectively under light load conditions, the throughput and probability of success of the CSMA protocols was better as the number of serviced devices per gateway increased. The average energy efficiency of the devices was observed to be better than the ALOHA in higher traffic loads

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*Delft, November 2018*

# Contents


**1 Introduction** **1**
1.1 Challenges in LoRa and LoRaWAN . . . 2
1.2 Thesis Question. . . . 2
1.3 Proposed Solution . . . 3
1.4 Contribution of Thesis . . . 3
1.5 Thesis Organization . . . 4

**2 Background and Literature Overview** **5**
2.1 LoRa . . . 5
2.1.1 Chirp Spread Spectrum . . . 5
2.1.2 Properties . . . 7
2.1.3 Time on Air (TOA). . . . 8
2.2 LoRaWAN . . . 9
2.2.1 Device Classes . . . 10
2.2.2 Packet Structure . . . 11
2.2.3 Communication Characteristics . . . 11
2.2.4 Downlink Characteristics . . . 13
2.3 Related work in LoRaWAN . . . 15
2.4 Related Work in CSMA . . . 15

**3 Carrier Sense Multiple Access in LoRaWAN** **19**
3.1 Regulations . . . 19
3.1.1 Regulatory Constraints . . . 19
3.1.2 Listen Before Talk . . . 20
3.2 LoRaWAN Protocol Constraints . . . 21
3.3 Carrier Sensing Protocols . . . 21
3.3.1 Hidden Terminal Problem . . . 23
3.3.2 Centralized Method . . . 24
3.3.3 Distributed Method . . . 25
3.3.4 Hybrid Method . . . 27
3.4 Network Stabilization Time . . . 28

**4 Carrier Activity Detection** **29**
4.1 CAD Functioning . . . 29
4.2 CAD Characteristics . . . 30
4.2.1 Timing . . . 30
4.2.2 Energy Consumption . . . 30
4.3 CAD Detection . . . 30
4.3.1 Experimental Setup . . . 31
4.3.2 Accuracy of Detection . . . 31
4.3.3 Sensing Range of Device with respect to Detection . . . 32
4.3.4 Sensing Range of Device with respect to RSSI . . . 34
4.4 Multiple Packets . . . 34
4.4.1 Detection of Data Rate for Single Packet . . . 35
4.4.2 Detection of Data Rate for Two Packets. . . . 36
4.5 Summary . . . 38

**5 Simulation and Results** **39**
5.1 MATLAB . . . . . . . . . . 39
5.1.1 Hidden Node Problem . . . . . . . . . . 39
5.1.2 Centralized Method . . . . . . . . . . 40
5.1.3 Distributed Method . . . . . . . . . . 42
5.1.4 Hybrid Method . . . . . . . . . . 44
5.2 NS3 . . . . . . . . . . 45
5.2.1 NS3 structure . . . . . . . . . . 45
5.2.2 Structure of code . . . . . . . . . . 46
5.3 NS3 Results . . . . . . . . . . 47
5.3.1 Centralized Method . . . . . . . . . . 47
5.3.2 Distributed Method . . . . . . . . . . 48
5.3.3 Hybrid Method . . . . . . . . . . 48
5.4 Summary . . . . . . . . . . 49

**6 Conclusion and Future Work** **51**

**Bibliography** **55**

# CHAPTER 1

# Introduction

In 1999, Kevin Ashton coined the term 'Internet of Things' to discuss a smarter packaging system which linked RFID information to the internet. The idea of connecting small day-to-day objects to create a smarter environment is simple yet powerful. In an article for the RFID journal in 2009 Ashton wrote, *"If we had computers that knew everything there was to know about things - using data they gathered without any help from us — we would be able to track and count everything, and greatly reduce waste, loss and cost. We would know when things needed replacing, repairing or recalling, and whether they were fresh or past their best"*[1].

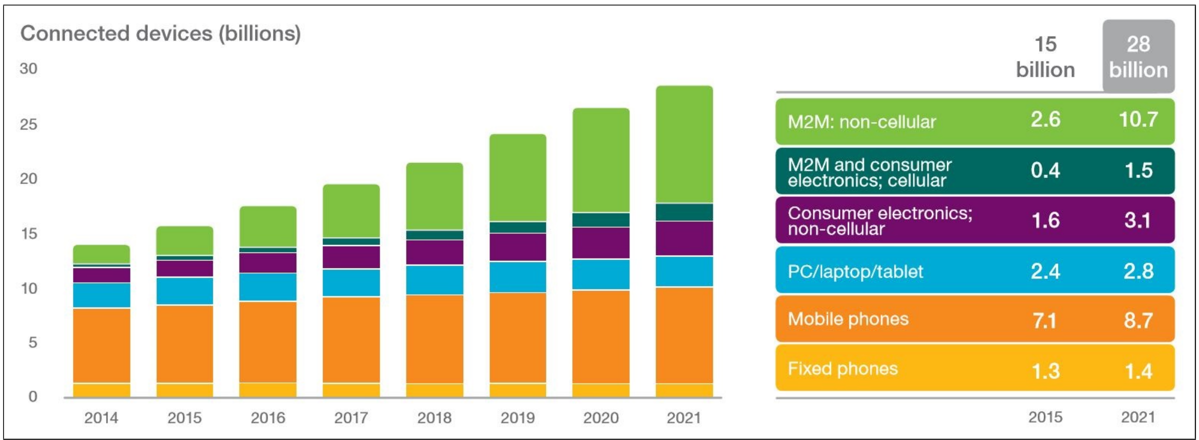



Figure 1.1: Prediction regarding connected IoT-devices of different types [2]

Growth in the field of Internet of Things (IoT) has opened up avenues for advancements in almost every walk of life such as smarter industries, cities, agriculture, creating the needs for monitoring and sensing networks spread over large ranges with minimal maintenance costs. While current communication technologies have advanced greatly, range and high power consumption problems still exist. These result in devices with a shorter battery life and increased costs. As the world becomes increasingly connected, the number of devices being serviced by a network increases rapidly. In 2017 over 217 devices were produced per minute. More devices mean higher power consumption. This is why Low-Power Wide-Area Network (LPWAN) technologies emerged. LPWANs wirelessly interconnect low-bandwidth, battery-powered devices with low bit rates over long ranges.

Unlike standard Wide Area Network (WAN) protocols, LPWANs transmit at low bitrate, typically between 0.3 kbit/s to 50 kbit/s per channel [3]. Popular examples of LPWANs include NB-IoT, LoRaWAN and Sigfox [4]. Many industries are deploying LoRa tracking systems to enable smarter and more efficient system process monitoring. LoRa is being used for a wide variety of applications across varied sectors; radiation & leak detection, smart sensor technology, shipping & transportation, agriculture, tracking patients suffering from Alzheimer's who are otherwise very likely to get lost, air quality & pollution monitoring, smart metering, parking & vehicle management, fire detection and waste management, among numerous others. Other exciting opportunities are being explored in many fields like mining, oil explorations and defense communications & installations.

LoRa enables transmission of data over large distances with low power consumption. It is a patented wireless communication technology. It was developed by Cycleo of Grenoble, France, and acquired by

Semtech in 2012. LoRa uses the unlicensed sub-gigahertz frequency bands of 433 MHz, 868 MHz (Europe) and 915 MHz (North America) for transmission.

## 1.1. Challenges in LoRa and LoRaWAN

LoRa technology is divided into two sections - the LoRa physical layer (LoRaPHY) and the LoRa network layer (LoRaWAN). The LoRa physical layer modulation is based on Chirp Spread Spectrum (CSS). In digital communications, CSS is a spread spectrum technique that uses wideband linear frequency modulated chirp pulses to encode information. CSS pulses are robust against noise and multi-path fading due to high Bandwidth-Time (BT) Product. They also allow for larger range of communication at low transmission power. These attributes are what make it suitable for LoRa. A downside of CSS is that for lower bandwidths the datarate is low, leading to longer time required for transmission.

LoRa devices are categorized as Short Range Devices (SRD) and operate in the unlicensed ISM band. As this research has been performed in the EU region it is subject to its regulatory standards. LoRa devices use 863 MHz to 870 MHz frequencies for transmission. The ERC/REC 70-03[5] document provided by the Electronic Communications Committee (ECC), defines the limitations of channel usage that the devices must adhere to. The salient points of these regulations are:

- Depending on the channel devices must adhere to a 0.1%, 1% or 10% duty cycle limit.
- For most channel transmission power of the devices cannot exceed 25mW.

These regulations limit the total Time on Air (TOA) spent for a transmission by each device, thereby limiting the maximum number of packets that the device can transmit in one hour.

LoRaWAN defines the communication protocol and system architecture of the network. Protocol and network architecture are the major contributing factors in determining network capacity, battery life, Quality of Service (QoS), security and applications served by the network. The star-topology network architecture has been implemented in LoRaWAN. The use of single hop network minimizes the energy spent by devices for communicating a single packet, thereby allowing for longer battery life. Nodes in the network transmit asynchronously when they have data ready to send. Data can be generated in an event-driven or scheduled manner. This type of Media Access Control (MAC) protocol is called ALOHA. Due to the asynchronous nature of ALOHA, packets transmission in the network occurs randomly. If two packets are transmitted simultaneously they will collide resulting in the loss of both packets. As the number of devices transmitting packets increases within a network, the probability of collision increases, thereby reducing channel throughput. Channel throughput is defined as the sum of successfully received packets within a specified time.

The challenges present in LoRa and LoRaWAN can be summarized as follows:

1. Large TOA requirements due to CSS.
2. Duty cycle limitations due to regulatory constraints in the EU.
3. Channel throughput efficiency reduction due to ALOHA protocol.

## 1.2. Thesis Question

Scalability is the capability of the network to adapt to an increasing number of devices being serviced. The challenges outlined above limit the number of devices that can be serviced by a single gateway using a single channel, thus limiting the scalability of the network. As the modulation technique or regulatory constraints cannot be changed nor circumvented, this thesis attempts to scale LoRaWAN by adopting medium access strategies that overcome the shortcomings of ALOHA, leading to the thesis question:

**"What is the MAC layer protocol that optimizes channel utilization in a LoRaWAN?"**

Scaling LoRaWAN is important for deployment and long-term usage. This creates the need for improving the current protocol so as to increase overall throughput and channel utilization. Implementing time synchronization and carrier sensing protocols are well-known solutions that overcome the shortcomings of ALOHA. However, as LoRa nodes and the transmission protocol itself is asynchronous, time synchronous protocols cannot be implemented to increase channel utilization. Also, LoRa does not provide for carrier sensing mechanisms that would allow for higher channel usage.

## 1.3. Proposed Solution

Several MAC protocols have been introduced to overcome the shortcomings of ALOHA. Some of these are Slotted ALOHA, MS-ALOHA, R-ALOHA and CSMA. Slotted ALOHA, MS-ALOHA and R-ALOHA require time synchronization between transmitting devices. Transmission can only start at the beginning of a discrete timeslot. As this goes against the inherent asynchronous nature of LoRaWAN, the aforementioned protocols have not been studied in this thesis.

Carrier Sense Multiple Access (CSMA) is a MAC protocol in which a node verifies the absence of other traffic before transmitting on a shared transmission medium. Devices in the wireless network listen (Carrier Sense) before transmitting. If the channel is in use, devices wait before transmitting. MA (Multiple Access) indicates that many devices can connect to and share the same network. All devices have equal access to the network when it is idle. There are three types of CSMA Protocols; 1-persistent, Non-persistent and p-persistent. Adopting CSMA techniques reduce the probability of collision, increasing the maximum number of packets serviced by a network.

The most popular CSMA protocols rely on handshaking or busy-tone mechanisms before transmitting a packet to ascertain if the channel is idle. LoRaWAN does not provide for this process. However, LoRa devices have inbuilt Carrier Activity Detection (CAD) capabilities. It is designed to detect a LoRa preamble on the radio channel with the best possible power efficiency. This can be used for sensing purposes. This work focuses on applying CAD as a sensing mechanism in combination with a persistent Carrier Sense Multiple Access (p-CSMA) or non-persistent Carrier Sense Multiple Access (np-CSMA) protocol to existing LoRaWAN. The research objectives are:

- Study and implement CAD as the sensing mechanism used in LoRaWAN.
- Study and compare various CSMA protocols.
- Adapt and implement p-CSMA and np-CSMA in LoRaWAN.

The following steps were undertaken to realize these objectives:

1. Identifying multiple LoRaWAN network scenarios based on differences in behavior of end-devices and gateways.
2. Assessing feasibility of implementing carrier sensing algorithms.
3. Adapting np-CSMA and p-CSMA techniques to each network scenario.
4. Studying the capabilities and limitations of CAD as a sensing mechanism by use of documentation and experiments and incorporating the identified results into the proposed network scenario options.
5. Testing the algorithms using event-driven simulations in MATLAB and NS3 environments.
6. Analyzing results to determine the effectiveness of the algorithms by comparing throughput and energy consumption of each protocol and scenario combination.
7. Comparing the proposed algorithms against traditional LoRaWAN to ascertain that the research goal is achieved.

## 1.4. Contribution of Thesis

This thesis addresses the challenges faced by a traditional single channel single gateway LoRaWAN under high traffic conditions by implementing a carrier sensing protocol. The major contributions are:

- Building algorithms to help maximize the network capacity.
- Defining the various network scenarios and their behavior when implementing the proposed algorithms.
- Incorporating the effects of imperfect sensing due to limitations arising from use of CAD mode as a carrier sensing mechanism.

## 1.5. Thesis Organization

The thesis report is divided into 6 chapters:

- Chapter 1 defines the motivation and challenges of this thesis project. It outlines the proposed solution and the contributions made through this work.
- Chapter 2 provides a brief introduction to LoRa and LoRaWAN technology. It describes the literature survey conducted to understand the characteristics and scalability constraints in LoRaWAN.
- Chapter 3 explains the problems related to scalability in LoRaWAN. It details the various network scenarios and the proposed algorithms to increase network throughput.
- Chapter 4 covers the studies and experiments performed to understand the working and limitations of CAD as a sensing mechanism.
- Chapter 5 describes the simulation outputs of the algorithms proposed in Chapter 3. It also incorporates CAD results based on the experimentation and observation from Chapter 4.
- Chapter 6 concludes the defined problem. It briefly discusses the results and contributions of the work and outlines recommendations for future work.

CHAPTER 2

# Background and Literature Overview

The unique capabilities of LoRa and LoRaWAN protocol - high performance, low power and affordable connectivity - make it ideal for use in applications requiring long range machine-to-machine connectivity. The focus of this work is to scale the number of connected devices to allow for increased channel throughput while still maintaining energy efficiency.

This chapter introduces LoRa and LoRaWAN and presents the literature review. It is divided in 4 sections:

- Section 2.1 is an introduction to the physical layer aspects of LoRa technology that are relevant to this work.
- Section 2.2 is an overview of the LoRaWAN technology. It discusses attributes like packet structure, communication characteristics, downlink processes, etc.
- Section 2.3 briefly discusses the current research in scalability and network capacity in LoRa and LoRaWAN.
- Section 2.4 compares the carrier sensing techniques and characteristics that are most relevant to this work.

## 2.1. LoRa

This section details the Chirp Spread Spectrum (CSS) based nature of LoRa. Next, some properties of LoRa. Finally, the time that a packet transmission takes is discussed.

### 2.1.1. Chirp Spread Spectrum

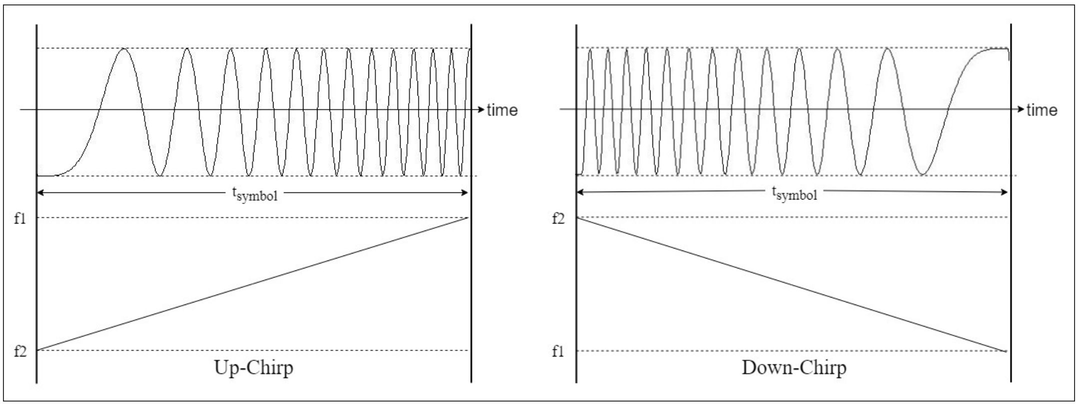



Figure 2.1: Up-Chirp and Down-Chirps

The LoRa physical layer is based on Chirp Spread Spectrum (CSS) modulation. Packets in CSS are encoded by means of CHIRP pulses which use wideband linear frequency modulation. CHIRP stands for 'Compressed High Intensity Radar Pulse'. It is a gradual change in the frequency over time. CHIRPs are of two types: Up-CHIRP and Down-CHIRP (Figure 2.1). In an up-CHIRP the frequency gradually increases over time. For a down-CHIRP the frequency decreases over time.

A CHIRP signal has a constant amplitude and is spread over the entire bandwidth in a linear fashion. CSS occupies the complete bandwidth when transmitting a packet. This makes it robust against channel noise, multi-path fading and the Doppler Effect. CSS relies on the linear nature of the chirp to distinguish between noise and data on the channel, thereby enabling it to work below the noise floor and making it suitable for LoRa modulation. LoRa is able to generate a stable CHIRP using a fractional-N Phase Locked Loop (PLL).

A LoRa modulated signal depends on the following key transmission parameters:

- Spreading Factor (SF): Spreading Factor is the number of chips per data symbol. As the spreading factor increases the Datarate (DR) decreases. LoRa modulation offers several different SFs, ranging from 6 to 12.

- Bandwidth (BW): Bandwidth is the frequency range used for modulation. LoRa modulation offers the use of multiple bandwidths, ranging from 7,800 Hz to 500,000 Hz. The most commonly used bandwidth in the EU is 125,000 Hz.

- Coding Rate (CR): Coding rate refers to the proportion of transmitted bits that actually carry information. A variable error correction scheme is used to improve the robustness of the transmitted signal. The values for CR range from 1 to 4. The $RateCode$ is hence given by

$$Rate\ Code = \frac{4}{4 + CR} \tag{2.1}$$

  Increasing the CR from $\frac{4}{5}$ to $\frac{4}{8}$ increases the transmit time by 27% but improves reception by 1 to 1.5 dBm, representing a potential range improvement of 12% to 18%.

LoRa chirp signals are generated by continuously varying the frequency. A signal uses the entire frequency bandwidth for the spread spectrum. The chip rate of a data signal is higher than the modulated chirp signal or symbol rate. The relation between the two is as follows:

$$R_b = SF \times \frac{1}{\frac{2^{SF}}{BW}}\ bits/sec$$

$$R_c = \frac{BW}{2^{SF}}\ symbols/sec \tag{2.2}$$

Hence,

$$R_c = R_s \times 2^{SF} \tag{2.3}$$

Therefore, the nominal bitrate is given by

$$R_b = \frac{Rate\ Code}{\frac{2^{SF}}{BW}}\ bits/sec \tag{2.4}$$

A LoRa signal consists primarily of three sections: Preamble, Sync symbols and Data, as can be observed in Figure 2.2. The first part of the message is the preamble. Preamble symbols are all up-chirps. The preamble length is programmable in the range of 2 to 65535 symbols. They are followed by Sync symbols, which are 2 $\frac{1}{4}$ symbols of down-chirps. The message is then transmitted in the form of a variety of up-chirps. The SF signifies the number of bits transmitted per symbol. If the SF is 7, 7 bits are transmitted over one symbol.

The LoRa chirp is divided into steps. At the receiver, the message is multiplied with an inverse chirp to extract its frequency. After performing Fast Fourier Transform or Discrete Fourier Transform on the received frequencies it is possible to separate the high energy symbols from the message. These high energy symbols constitute the data content in the message.

LoRa nodes are equipped with a 256 byte RAM data buffer called a FIFO. It is fully customizable by the user and allows access to the received, or to be transmitted data. All access to the LoRa FIFO data buffer is done via the Serial Peripheral Interface (SPI).

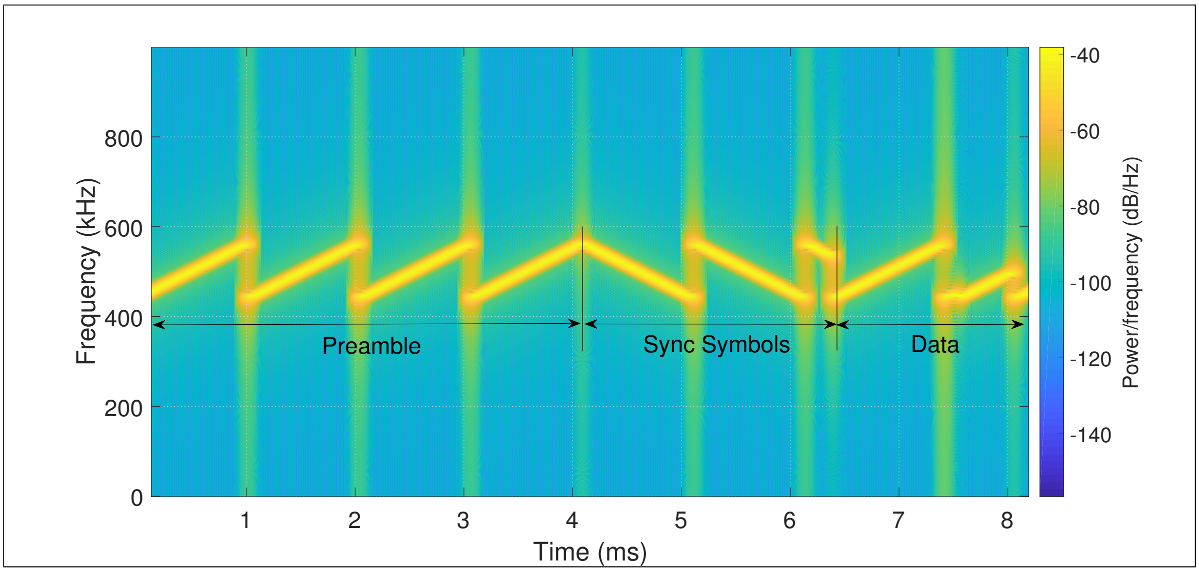



Figure 2.2: LoRa Packet

LoRa devices function in eight operating modes:

- **SLEEP**: This is the Low-Power Mode. The FIFO is not accessible.
- **STAND-BY**: The crystal oscillator and LoRa baseband are turned on. The FIFO can be accessed and written in this mode.
- **FSTX**: This is a frequency synthesis mode for transmission. The PLL selected for transmission is locked and active at the transmit frequency.
- **FSRX**: This is a frequency synthesis mode for reception. The PLL selected for reception is locked and active at the receive frequency.
- **TX**: The radio module (RF) is turned on and transmission occurs in this mode. After the transmission is complete, the device is switched to STAND-BY mode.
- **RXSINGLE**: All the reception blocks are powered and after a packet is received, the device enters STAND-BY mode.
- **RXCONTINUOUS**: All reception blocks are powered and the device receives packets until a new user request is made to change the operating mode.
- **CAD**: Carrier Activity Detection allows a device to listen to a particular channel to detect the presence of a LoRa preamble.

### 2.1.2. Properties

LoRa modulation method has several advantages over traditional LPWANs.

- Bandwidth and frequency are easily scalable in LoRa modulation, making it easy to adapt for narrow-band frequency hopping and wideband direct sequence applications.
- Like Frequency Shift Keying (FSK), LoRa is a constant envelope modulation technique. It can apply low-cost and low-power high-efficiency Power Amplifier stages. The processing gain can be reduced to improve the link budget.
- Due to the inherent CSS property of a high BT product, LoRa is resistant to interference. As chirp pulses are broadband they are resistant to multi-path fading.

- Doppler shift causes a small frequency shift in the LoRa pulse which introduces a relatively negligible shift in the time axis of the baseband signal. This frequency offset tolerance mitigates the requirement for reference clock sources with tight tolerances.
- LoRa is resistant to interference and has a link budget better than FSK. This combination quadruples the communication range for LoRa making it ideal for long range communication.
- LoRa modulation offers multiple SF options orthogonal to each other, i.e. multiple simultaneous transmissions are possible on the same channel with minimum degradation in the received sensitivity.
- An inherent property of LoRa is the ability to linearly discriminate between frequency and time errors. It is the ideal modulation for radar applications and is thus well suited for ranging and localization applications such as real-time location services.
- LoRa modulation method ensures that the frequency and timing offsets of the transmitter and receiver are equivalent, making the receiver design less complex.

The data rate of LoRa modulation is lower than Wi-Fi or Bluetooth. The bitrate can vary from 11.43 bit/s for SF12 and BW 7.8 kHz to 21,875 bit/s for SF7 and BW 500 kHz. In the EU the most common data rates used for transmission range from DR0 to DR6. Their configuration is provided in Table 2.1. The CR is kept at 1 which gives a $Rate\ Code$ of $\frac{4}{5}$.

| Datarate | Spreading Factor | Bandwidth (kHz) | bitrate (bps) |
|---|---|---|---|
| 0 | 12 | 125 | 290 |
| 1 | 11 | 125 | 540 |
| 2 | 10 | 125 | 980 |
| 3 | 9 | 125 | 1760 |
| 4 | 8 | 125 | 3125 |
| 5 | 7 | 125 | 5470 |
| 6 | 7 | 250 | 10940 |

Table 2.1: Datarate and corresponding bitrates

### 2.1.3. Time on Air (TOA)

TOA is the time required by a device to transmit a single packet. Due to low transmission data rates, the TOA spent by a packet can be large. Given the duty cycle regulations in the EU, having large TOA reduces the maximum number of packets transmitted per device, thereby limiting channel efficiency. The formulae are provided in the Semtech documentation [6] and are as follows:

The first step is calculating the *symbol duration* $T_{sym}$

$$T_{sym} = \frac{2^{SF}}{BW} \tag{2.5}$$

The *preamble time* $T_{pr}$ is generated by

$$T_{pr} = (n_{pr} + 4.25) \times T_{sym} \tag{2.6}$$

where,
$n_{pr}$ is the programmable preamble length.

Next, the *payload time* $T_{py}$ is calculated

$$n_{py} = 8 + \quad max\left(\left\lceil \frac{8 * PL - 4 * SF + 28 + 16 - 20 * H}{4 * SF - 8 * DE} \right\rceil (CR + 4), 0\right) \tag{2.7}$$

$$T_{py} = n_{py} * T_{sym} \tag{2.8}$$

where,
PL is Payload bytes,
H is Header Enable/Disable,
DE is Low DataRate Optimization Enable/Disable.

Finally, the two values $T_{pr}$ and $T_{py}$ are added to get $TOA$

$$TOA = T_{pr} + T_{py} \tag{2.9}$$

## 2.2. LoRaWAN

LoRa Wide Area Network (LoRaWAN) is the network layer protocol for devices performing LoRa modulation. It uses the unlicensed ISM band for low power long distance communication between sensor devices and gateways. It is end-to-end Advanced Encryption Standard (AES) secure.

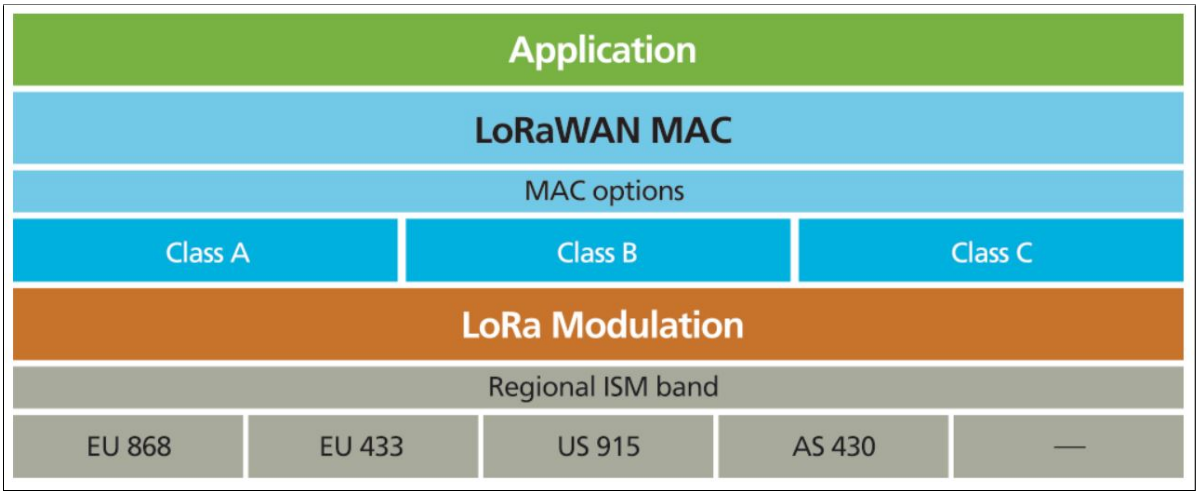



Figure 2.3: LoRa Stack [7]

The LoRa Stack is illustrated in Figure 2.3, with layers being:

- The carrier frequency used by LoRa modulation depends on the region. In the EU 868 MHz the frequency band is used. The physical layer modulation transmitting on the carrier frequency is detailed in Section 2.1.
- The MAC layer protocol of LoRaWAN controls how and when transmission occurs in a network. The basic network flow can be observed in Figure 2.4. The end-devices belonging to either Class A/B/C transmit data to gateways.
- Gateways are connected to a network server which processes the packet received by each gateway. If the network ID is as expected, the message is forwarded to the application layer. Else, the received message is discarded.
- In the application layer the payload information can be retrieved, stored or processed further.

LoRaWAN gateways relay messages to a backend network server via TCP/IP connections. Gateways and devices use multiple channels and data rates for communication. Communication in LoRaWAN is bi-directional, but most of it is uplink data from the end-devices to the network server. LoRaWAN communication is based on ALOHA protocol. The gateway acts as the central hub and the end-devices are the hosts. LoRaWAN devices use unslotted ALOHA for transmission, i.e. if the end-device is ready to transmit a packet, it will.

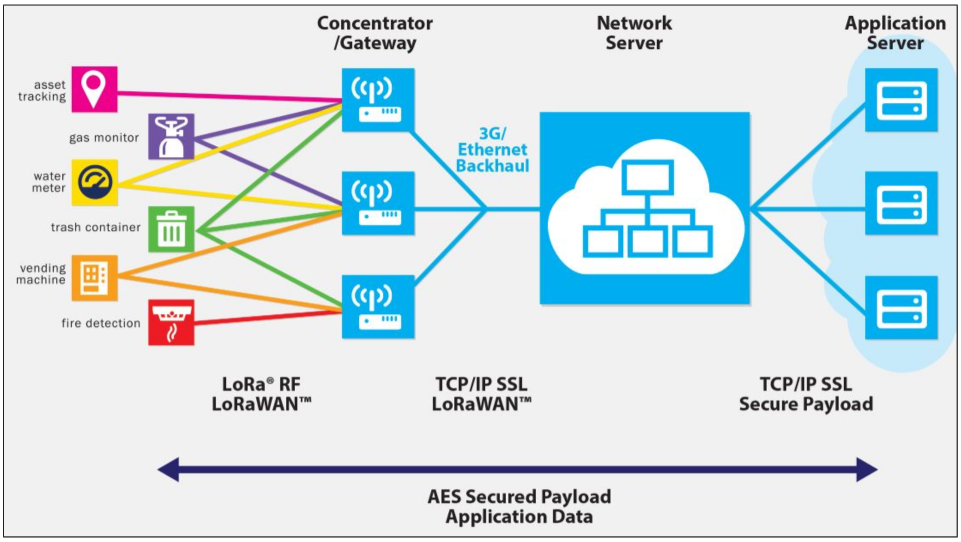



Figure 2.4: LoRa Network Overview [7]

### 2.2.1. Device Classes

LoRa devices can be sensor nodes or gateways. They are divided into three classes. The differences can be better understood by referring to Figure 2.5.

- **Class A bi-directional end-devices**: These devices are predominantly used for uplink transmission, which is followed by two short downlink receive windows. Class A devices are intended for use in applications requiring minimum downlink communication from the network server and can only be scheduled after an uplink transmission. Typically a downlink receive window is opened for 1 second. If information is received in the first slot, the second downlink window is not opened.

- **Class B bi-directional end-devices with scheduled receive slots**: Class B devices operate similar to Class A devices but they open extra scheduled downlink receive windows. To do so, a device receives a time synchronized beacon from the gateway. The power requirements of Class B devices are higher than those of Class A devices.

- **Class C bi-directional end-devices with maximal receive slots**: Class C devices almost always have a receive window open. It is closed only when the device is transmitting. The power requirements of the devices are the highest. Class C devices offer the lowest latency for server to end-device communication.

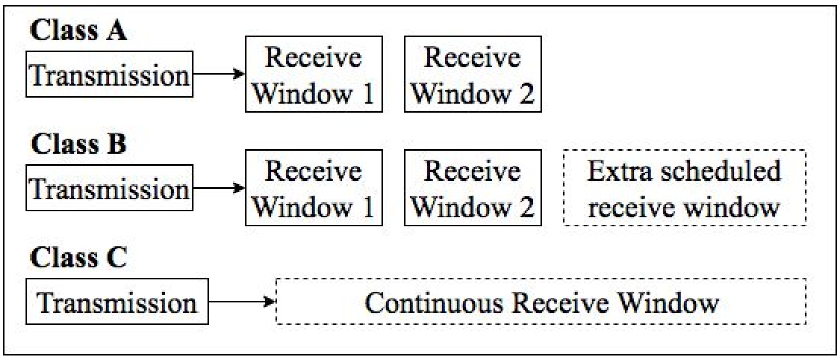



Figure 2.5: LoRa Device Classes

As Class A devices are most widely used, this thesis concentrates on these type of devices for experimentation.

### 2.2.2. Packet Structure

A LoRa packet can be of two types: uplink or downlink. The structure of a LoRa packet can be observed in Figure 2.6. Any uplink or downlink message carries a physical (PHY) payload. This payload consists

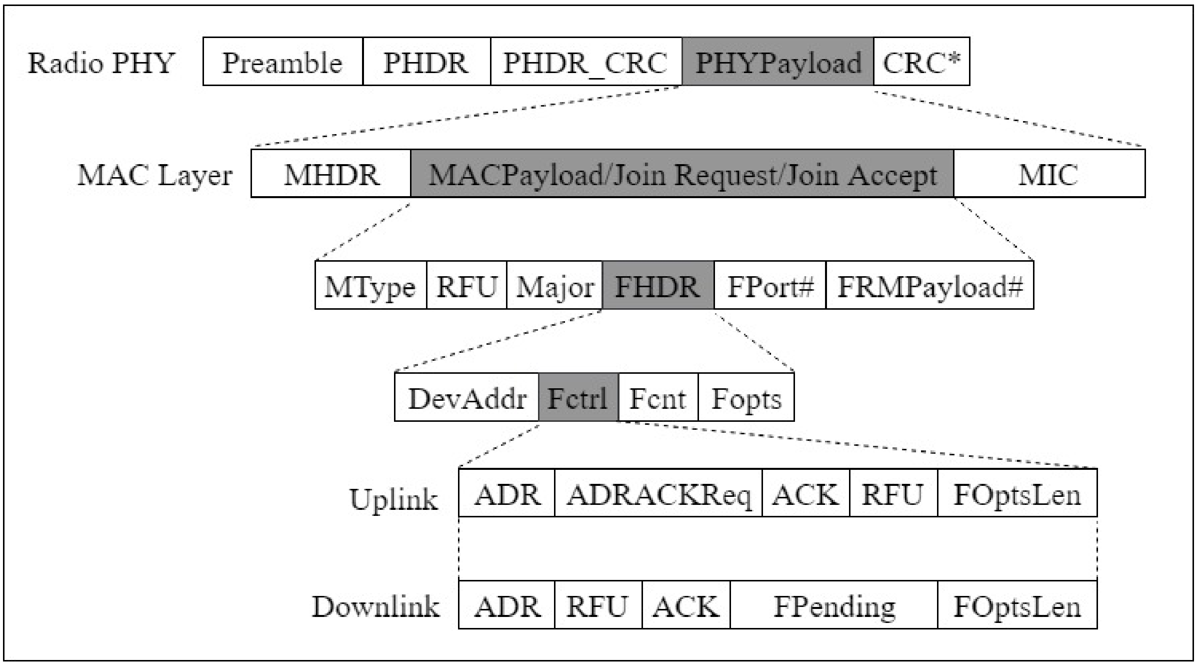



Figure 2.6: LoRa Packet Structure [8]

of the MAC header, payload and message integrity check (MIC). The LoRa radio packet starts with a preamble followed by a physical header (PHDR) and its corresponding physical header cyclic redundancy check (PHDR_CRC). This PHDR_CRC is followed by the physical payload and then finally by the payload CRC. The PHDR, PHDR_CRC and the CRC are inserted into the radio PHY by the transceiver. The payload CRC is discarded in a downlink message.

The next layer is the MAC layer. It consists of an 8 byte MAC header (MHDR) followed by the MAC payload and finally a 4 byte MIC. The MAC payload will differ based on the type of message. A device attempting to connect to a network transmits a Join Request (JR). If a gateway accepts the device as valid it will transmit a Join Accept (JA). If the message being transmitted is a data message it is placed in the MAC payload field. The type of message being transmitted is decided by the value of the 3 bits of message type (MType). If the message is a JR, the MType field contains 000. For JA it is 001. 010 is used for unconfirmed data uplink. The next field called major, specifies the format of the messages exchanged during the joining process. This field enables the gateway to decide if the message is supported by its corresponding LoRaWAN network server. The frame port (FPort) field dictates if the message received is accessible to the MAC layer or the application layer. If FPort value is equal to 0 the frame payload (FRMPayload) contains the MAC commands and is then processed by the LoRaWAN implementation. If the FPort value lies between 1 and 223 the received frames are made available to the application layer in the LoRaWAN.

### 2.2.3. Communication Characteristics

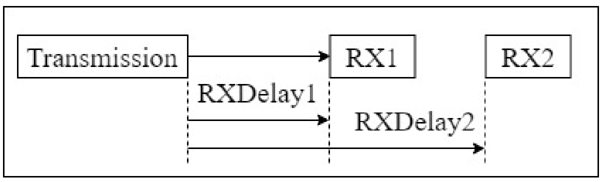



Figure 2.7: LoRaWAN Transmission at End-Device

Figure 2.7 shows the transmission and reception behavior of an end-device. After transmission of a packet the device waits for a time delay of RXDelay1 before opening the first RX window. If the downlink message is not received or is incomplete a second RX window is opened after a time delay of RXDelay2. Typically RXDelay1 is 1s and RXDelay2 is 2s. These values can be adjusted in the JA frame.

Transmission or reception of data is enabled by setting the device into TX and RX modes respectively. The following is a list of registers that must be written for the correct functioning of a LoRa device. All the registers contain 8 bits each.

- RegOpMode: LoRa devices can switch between LoRa and FSK mode. Setting bit 7 enables LoRa mode. Bits 2-0 control the current LoRa operating mode.
- RegModemConfig1: The BW and CR values are initialized in the register. The implicit/explicit use of the header is also defined here.
- RegModemConfig2: The SF is set by writing bits 7-4 in this register. Optional RX_CRC can also be enabled.
- RegPreambleLSB and RegPreambleMSB: These registers store the programmable preamble value.
- RegIrqFlags: This register holds the following interrupt flags
  - RxTimeout: Timeout interrupt.
  - RxDone: Packet reception complete interrupt.
  - PayloadCrcError: Payload CRC error interrupt.
  - ValidHeader: Valid header received in Rx.
  - TxDone: FIFO Payload transmission complete interrupt.
  - CadDone: CAD complete.
  - FhssChangeChannel: Frequency hopping spread spectrum (FHSS) change channel interrupt.
  - CadDetected: Valid LoRa preamble detected during CAD operation.

  For all interrupts, writing a 1 clears the interrupt (IRQ).

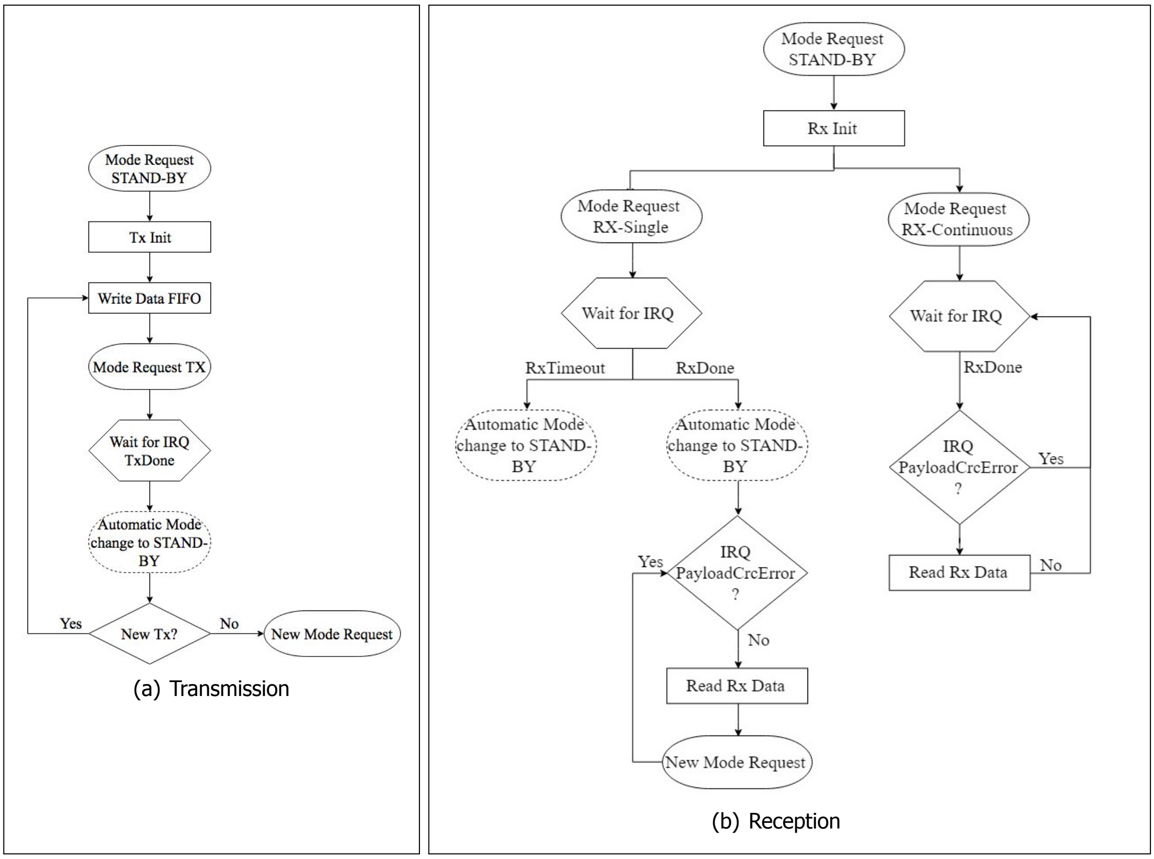
Devices are configured with the required parameters before transmission or reception of a packet. Once configured, the devices only need reconfiguration if parameters change. The following are the steps performed to initialize a device:

- The device must be set in LoRa STAND-BY mode by writing the RegOpMode.
- RegModemConfig1 and RegModemConfig2 are written with the required SF, CR and BW along with other optional features like implicit/explicit header mode and low data rate optimization mode.
- The programmable preamble length is written into the registers RegPreambleLSB and RegPreambleMSB.
- Transmission or reception then begins by setting the RegOpMode into the appropriate operating mode.
- The RegIrqFlags register is monitored to stop the transmission and reception processes and return the device to STAND-BY mode.

The transmission and reception of data to and from a LoRa device are detailed in Figure 2.8. For transmission, TxDone flag is monitored in the RegIrqFlags. Once set, the device returns to STAND-BY mode and the flag is cleared.

Reception in LoRa can be of two types: RX-Single and RX-Continuous. Once the device is set into RX-Single mode it will wait until either the RXTimeout occurs or the RxDone flag is set. If RxTimeout is set, the device returns to STAND-BY mode. However, if the RxDone flag is set the PayloadCRCError flag is checked. If the payload is error-free the received data is decoded and the device enters STAND-BY mode. All flags are cleared.

In the case of RX-Continuous the device waits for the RxDone flag to be set. It then checks for a PayloadCRC error. If an error occurs, the device clears the RxDone flag, returns to reception mode, and repeats the process. If PayloadCRC error does not occur, the received data is decoded and the device returns to reception mode. This will continue until the mode change request occurs.




(a) Transmission

(b) Reception

Figure 2.8: TX/RX Processes in LoRaWAN [9]

### 2.2.4. Downlink Characteristics

The devices receive two types of messages from a gateway: Join Accept (JA) and Adaptive Data Rate (ADR). A JA is used when a device first establishes connection with the gateway. Once the gateway has verified the Join Request (JR) coming from the device as accurate, it will transmit a JA message to acknowledge the device as accepted and connected.

ADR is used by the gateway to update and optimize the transmission configuration. In the proposed model, ADR and JA communication is used to provide gateway feedback to devices.
The first subsection explains the join process while the second elaborates the functioning of ADR.

#### Join Process

Any LoRa device undergoes a join process. Join processes can be of two types: Over-the-Air-Activation (OTAA) and Activation by Personalization (ABP). The differences in these processes are observed in Figure 2.9.

OTAA is an 'over the air' handshake joining process. It is outlined as follows:

- The device transmits its Device Extended Unique Identifier (DevEUI), Application Extended Unique Identifier (AppEUI) and Application Key (AppKey) in a JR message. These fields are configured at initialization.
- The gateway authenticates the received information and upon success will transmit a JA containing the Device Address (DevAddr), Application Session Key (AppSKey) and Network Session Key (NwkSKey).
- The device is then able to transmit data packets.

In ABP, an over the air join process is not necessary as the DevAddr, AppSKey and NwkSKey are configured at initialization. The session keys are generated from time to time to ensures the security of the communication. These differences are why OTAA is recommended for node configuration in a real world setting, while ABP is preferred for testing purposes.

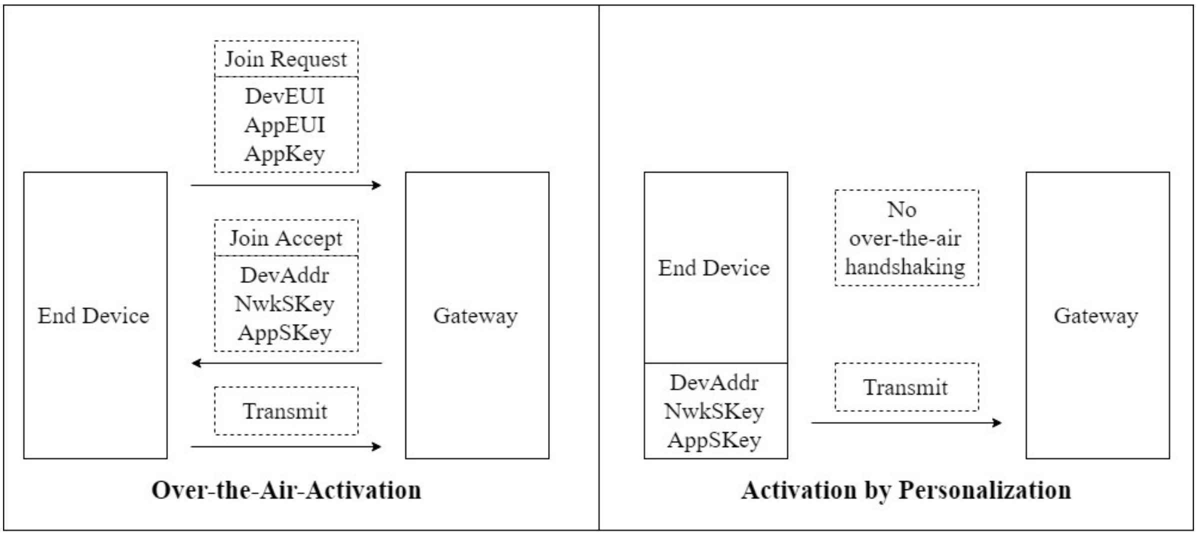



Figure 2.9: LoRaWAN Join Processes

### Adaptive Data Rate

LoRaWAN allows end-devices to select their transmission power and data rates. Additionally, it allows the network to control these parameters to optimize the power and TOA requirements of the device. ADR is built specifically for this purpose. When an end-device wishes to follow ADR, it sets the ADR bit during the transmission of an uplink message. The gateway will record the $SNR_{max}$ for 20 consecutive received messages. $SNR_{margin}$ is calculated using the following formula:

$$SNR_{margin} = SNR_{max} - SNR_{required} - margin \tag{2.10}$$

where,
$SNR_{required}$ depends on the current data rate of the message,
$margin$ = 10.

The $SNR_{required}$ corresponding to the data rate is detailed in Table 2.2.

| Datarate | $SNR_{required}$ (dB) |
|---|---|
| 0 | -20 |
| 1 | -17.5 |
| 2 | -15 |
| 3 | -12.5 |
| 4 | -10 |
| 5 | -7.5 |

Table 2.2: $SNR_{required}$ used by ADR algorithm

$SNR_{margin}$ is then used to calculate $Nstep$ using the formula

$$Nstep = \left\lfloor \frac{SNR_{margin}}{3} \right\rfloor \tag{2.11}$$

If Nstep > 0: Increment the transmission power in each step by 3, until the maximum power (-17dB) is reached.
If Nstep < 0: Increment DR in each step until DR5 is reached. Decrement transmission power in each step until minimum transmission power is reached.
The end-device using ADR will try to validate whether the network is receiving its corresponding uplink messages. Whenever the end-device sends a frame, it increments frame counter and an ADR_ACK_CNT counter. If ADR_ACK_CNT equals ADR_ACK_LIMIT (64 frames) it sets the ADRACKReq bit to 1 and asks

the network if the uplink messages are being received. The network must reply within ADR_ACK_DELAY (32 frames) time. If an acknowledgement is received, the ADR_ACK_CNT is reset. If downlink is not received, the end-device will decrease its data rate step by step until minimum data rate is reached.

## 2.3. Related work in LoRaWAN

This section provides a brief overview of the work done towards understanding scalability in LoRaWAN.

The work by Mikhaylov et. al. [10] analyzes the capacity and scalability of LoRa LPWANs. The authors have derived performance metrics to study uplink throughput and data transmission time for single LoRaWAN end-devices. They examined the effects that acknowledgements and distance from a single base station have on the capacity and data transmission rates of the uplink channel. They concluded that for LoRaWAN to be scalable, the number of devices at large distances must be minimal. Also, acknowledgements and receive windows can cause substantial delays in the transmission of packets leading to poor performance and reliability. The authors assume that LoRaWAN follows unslotted ALOHA transmission protocol.

Georgiou and Raza [11] use a stochastic geometry framework for modelling the performance of a single gateway in a LoRaWAN following ALOHA and duty cycle limitations. They provide two link outage conditions; one which relates to SNR and the other which relates to co-spreading sequence interference. They conclude that in spite of the various interference mitigation models in LoRa, performance decreases exponentially with an increase in end-devices. They attribute this majorly to co-spreading factor interference. Finally, they state that studies are greatly restricted due to lack of appropriate simulation software.

The work by Bor et. al. [12] simulates LoRaWAN using a custom build discrete event simulator implemented using SimPy. They work in a 2D environment with a single gateway as the center and a random distribution of devices around it. The simulator tests the serviceable limits of the number of end-devices supported by a single one channel gateway. An ALOHA like protocol has been assumed for the network. The authors concluded that devices with higher SFs are not ideal as very few devices can be serviced. They recommended using multiple gateways and smaller SF to increase scalability. Assigning transmission parameters dynamically is the second method proposed to increase the scalability.

Varsier and Schwoerer [13] have developed a MATLAB simulation to study the effects of multiple gateways and downlink messages on a LoRa channel. The gateways in the network follow a hexagonal distribution with an Okumara-Hata propagation model. QoS and packet extraction rate (PER) are the two parameters used to test the scalability. They conclude that having downlink messages in a network greatly decreased the capacity of LoRaWAN.

The works ([3], [10], [12]) analyze LoRaWAN as an ALOHA protocol and attribute its scalability limitation to duty cycle restrictions and behavioral constraints of ALOHA LoRaWAN protocol. The research presented in [11] attributes lack of supported devices to co-spreading interference, which is contrary to orthogonality being a feature to increase scalability as stated in LoRa [14]. Some works like [13] and [10] also analyze the effects of using acknowledgements and downlinks in a network which reduces the available duty cycle limit, hence decreasing scalability.

This research takes into account these characteristics and attempts to implement a carrier sensing MAC layer protocol using CAD as the carrier sensing medium. An event-driven MATLAB simulator was developed which implements carrier sensing techniques.

## 2.4. Related Work in CSMA

The work by Kleinrock and Tobagi [15] introduces the concept of persistent and non-persistent CSMA. Their paper assumes that all nodes in the network have a constant packet length and are in Line of Sight (LoS) of each other. It mathematically proves that p-persistent and non-persistent CSMA will give higher throughput and channel utilization as compared to slotted and unslotted ALOHA. It also briefly explains that if hidden nodes exist in the system, the throughput would greatly decrease. This concept has been further researched and presented in a follow-up paper written by the same authors. The paper [16] presents the concept of using a busy-tone mechanism as a solution to the hidden node problem. This mechanism works by dividing the available bandwidth into two channels. One channel is used for packet transmission while the other is used for busy-tone transmission. All the transmitting nodes are assumed to be within listening range of the receiver station and vice-versa. The station sends a busy-tone when it is receiving a message from any of the nodes. Hence, all nodes can check the busy-tone channel before deciding to transmit a packet. If a busy tone exists, the node will wait before trying to re-transmit. Their paper applies this method to 1-persistent, 0.03 persistent and slotted/unslotted non-persistent CSMA to study the changes in the throughput and channel capacity. Their results showed that slotted non-persistent CSMA gives the best performance in a hidden node scenario.

The paper by Huang and Kleinrock [17] analyzes the throughput of a busy-tone CSMA network in the presence of noise. It studies the effect of a node detecting the channel to be idle, when it is in fact busy. This type of channel leads to imperfect sensing. A solution is presented in the form of an algorithm that waits a certain number of consecutive idle channel detects before attempting to transmit a packet. A mathematical analysis of throughput shows how this algorithm gives better channel capacity in a real world situation. The experiments in this paper are carried out only on non-persistent CSMA.

For wireless devices to increase the battery-life, a trade-off between accurate sensing and efficient energy consumption is vital. The paper by Ramachandran and Roy [18] focuses on this concept. It uses a transfer function approach to understand energy efficiency in a system with perfect sensing. For imperfect sensing an approximate analysis with some reasonable assumptions is presented. The results conclude that, given the statistics of imperfect sensing and the transceiver's complexity, it is possible to optimize energy efficiency.

The studies presented above assume that all nodes in the network are homogeneous. They all have the same offered load and transmit with the same p-persistent value. However, this condition cannot hold true in a real world situation. The paper by MacKenzie and O'Farrell [19] analyzes this aspect. It uses analytic models to understand heterogeneous loads and priorities in a non-saturated system and its effects on system performance. Finally, a throughput delay analysis for slotted p-persistent CSMA is presented. The results are validated through simulation of the network.

LoRaWAN devices are built using inexpensive components making them easily accessible for all. One of the major concerns with such devices is their inability to sense the channel correctly. A paper proposed by Kim et. al [20] attempts to understand and solve this problem. They have proposed a pre-emptive CSMA technique and analyzed throughput in the case of perfect and imperfect sensing. The pre-emptive CSMA algorithm proposed is similar to IEEE 802.11n CSMA/CA with RTS/CTS and frame aggregation. The major takeaway from the analysis was, that only false negatives failures result in throughput loss when sensing is imperfect. Assigning small access probabilities makes it possible to overcome the carrier sensing failures of devices in a network.

The paper by Duda et.al [21] tests CSMA in a NS3 simulator. They propose CSMA and CSMA-10 as the two sensing techniques to lower the collision ratio with minimal increase in energy consumption. They observe lower energy consumption as the number of devices increases using their proposed method when compared with traditional LoRaWAN for a large number of devices. The proposed work varies from this research in the way that it does not propose an actual sensing mechanism, but rather builds an algorithm and results in the case that a sensing mechanism existed. All the works presented above analyze a CSMA network with respect to one or more of the following attributes:

1. Heterogeneous 'p' value.
2. Imperfect sensing.
3. Asynchronous nodes.
4. No Requirement of ACKs.
5. Efficient Energy Consumption.

The model proposed in this work assumes a scenario satisfying all of the above points stated above. The papers [17], [18] [20] and [22] all assume that the CSMA network consists of nodes with a constant payload and p-persistent value. Only the paper by [19] studies a more real world example with heterogeneous offered load and p-value. Even if the payload size is constant, the different data rates indicate variable transmit times accounting for the heterogeneous load.

The next factor is imperfect sensing. The papers [17], [18] and [20] do not assume perfect sensing in a CSMA network. This is an important assumption affecting the throughput-delay model of the network. A sure method of achieving optimal output is by using a slotted system and synchronizing nodes. The papers [18], [19] and [20] assume that all nodes are synced and all transmissions are slotted. However, LoRa nodes are not synced and in this work it is assumed that they continue to work in an unslotted fashion. When dealing with asynchronous nodes it becomes necessary for the the system to use acknowledgements to guarantee packet delivery and QoS. The two works [17] and [22] which do not assume synchronization of nodes, use acknowledgements to provide accurate packet delivery and QoS. However, this is not an ideal condition in the current LoRa network due to duty cycle and energy limitations. A big advantage of LoRa nodes is their low power consumption allowing for a battery life lasting up to 10 years. Efficient energy consumption is therefore vital to such a network. For this the work by Ramachandran [18] was studied. It gives an understanding of the energy usage in a CSMA network. All the other works mentioned do not account for energy limitations of devices.

CHAPTER 3

# Carrier Sense Multiple Access in LoRaWAN

This chapter discusses the scalability problems faced by LoRaWAN and the proposed MAC layer implementations. A LoRa network is subject to several constraints, including:

- Duty cycle limitations from regulatory bodies.
- Channel utilization constraints due to ALOHA like network protocol.

These are the primary factors hampering scalability and throughput of the network. These constraints and possible solutions are outlined in this chapter. The first section discusses the limitations and solutions of the network with respect to regulatory constraints. The second section details scalability constraints of the current LoRaWAN MAC layer. The third section discusses the proposed solutions. Finally, the time that a network would take to reach an optimal value are characterized in the fourth section.

## 3.1. Regulations

In the EU, the allocation of ISM frequency bands and their use are based on recommendations by the Electronic Communications Committee (ECC), which is part of the European Conference of Postal and Telecommunication Administration (CEPT). The ECC document covering SRD is ERC/REC 70-03[5]. LoRa modules communicate in the 863-870 MHz frequency range. This imposes duty cycle and transmission power constraints. Table 3.1 details the restrictions on LoRa nodes for every frequency lying between 863-870 MHz.

| Frequency Band (MHz) | Maximum Effective Transmission Power (mW) | Duty Cycle Limitation | | Time Limit per Hour (seconds) |
|---|---|---|---|---|
| | | Duty Cycle | Listen Before Talk | |
| 863 to 865 | 25 | 0.1% | Polite spectrum access | 3.6 |
| 865 to 868 | 25 | 1% | " | 36 |
| 868 to 868.6 | 25 | 1% | " | 36 |
| 868.7 to 869.2 | 25 | 0.1% | " | 3.6 |
| 869.4 to 869.65 | 25 | 0.1% | " | 3.6 |
| 869.4 to 869.65 | 500 | 10% | " | 360 |
| 869.7 to 870 | 5 | No requirements | No requirement | - |
| 869.7 to 870 | 25 | 1% | Polite spectrum access | 36 |

Table 3.1: EU Regulatory Constraints for 863-870 MHz

### 3.1.1. Regulatory Constraints

Regulatory constraints cannot be circumvented. Having to adhere to duty cycle regulations greatly limits the number of devices that can be serviced by a single gateway. However, the use of a carrier sensing

| DataRate | Payload (Bytes) | Time on Air (ms) | Duty cycle 0.1% | Duty cycle 1% | Polite Spectrum Access | Duty cycle 10% |
|---|---|---|---|---|---|---|
| 0 | 2 | 827.39 | 4 | 43 | 120 | 435 |
| | 35 | 1810.43 | 1 | 19 | NA | 198 |
| | 52 | 2465.79 | 1 | 14 | NA | 145 |
| 1 | 2 | 412.7 | 8 | 87 | 242 | 872 |
| | 35 | 987.17 | 3 | 36 | 101 | 364 |
| | 52 | 1314.82 | 2 | 27 | NA | 273 |
| 2 | 2 | 206.85 | 17 | 174 | 483 | 1740 |
| | 35 | 534.53 | 6 | 67 | 187 | 673 |
| | 52 | 739.33 | 4 | 48 | 135 | 486 |
| 3 | 2 | 103.42 | 34 | 348 | 966 | 3480 |
| | 35 | 308.22 | 11 | 116 | 324 | 1167 |
| | 52 | 410.62 | 8 | 87 | 243 | 876 |
| 4 | 2 | 61.95 | 58 | 581 | 1614 | 5811 |
| | 35 | 174.59 | 20 | 206 | 572 | 2061 |
| | 52 | 225.79 | 15 | 159 | 442 | 1594 |
| 5 | 2 | 30.98 | 116 | 1162 | 3227 | 11620 |
| | 35 | 97.54 | 36 | 369 | 1025 | 3690 |
| | 52 | 133.38 | 26 | 269 | 749 | 2699 |

Table 3.2: Maximum possible packets transmitted by a device when using different regulation constraints

mechanism can help increase the individual throughput of the device using Listen Before Talk (LBT), while also minimizing the chances of collision. The number of packets is derived from the equation probability of success for ALOHA networks, which is an exponential value depending on number of devices, TOA and transmission rate ($\lambda$). N is calculated by using the formula:

$$N = \frac{log_{10}(P_s)}{-2 \times \lambda \times TOA} \tag{3.1}$$

where,
N is the number of devices,
$\lambda$ is defined by the duty cycle and is in seconds,
TOA is the time on air of a single transmission by the device
$P_s$ is the probability of success. For reduced energy consumption and high QoS the expected $P_s$ is assumed to be 0.9.

Table 3.2 lists the maximum number of devices that can be serviced by a single gateway when adhering to the various duty cycle limitations stated in Table 3.1. For the different configurations depicted in the table the CR is 1 and the preamble is 8 symbols.

### 3.1.2. Listen Before Talk

LoRa devices are categorized as SRD. The ECC document covering SRD is EN 300 220-1 - V2.4.1 [23]. It states that if a carrier sense mechanism is used to access the channel it is possible to increase the maximum Time on Air (TOA) allocated to each device. This access method is called a Listen Before Talk or Polite Spectrum Access. LBT allows a device to access the channel for a maximum total TOA of 100s for a 200 MHz Bandwidth. For LoRa devices using BW 125 MHz it equals a maximum total TOA of 62.5s. This gives a 73.6% increase in available TOA for any device running on a 1% duty cycle, implying a higher throughput for devices. LBT mechanism sets a constraint on the maximum continuous TOA for a device at 1s. This limits the usage of DR1 to some extent and DR0 to a large extent. LBT can be used by devices in all LoRaWAN channels without having to adhere to duty cycle restrictions. It helps to increase the probability of a message being successfully received by a gateway. LBT can be used by most DRs stated by LoRa. It assumes that the Received Signal Strength Indicator (RSSI) at the receiver must be greater than or equal to -96 dB for the channel to be idle. However, due to the receiver architecture of LoRa devices, packets with RSSI less than the stated value can also be decoded by gateways. Thus, this threshold cannot be used as a measure of channel state.

Implementing LBT increases the number of packets that can be transmitted by a device, which subsequently increases the total number of packets in the channel, thereby reducing the number of devices that a gateway can service. Hence LBT is not considered suitable to scale LoRaWAN and therefore has not been implemented in this work.

## 3.2. LoRaWAN Protocol Constraints

LoRaWAN uses an ALOHA like MAC layer protocol. If a node has a packet it will transmit. If two packets are transmitted simultaneously from two devices they will collide. Assuming that packet transmission in the network is a Poisson process at the rate of $G$ attempts per second, the probability of success $P_s$ i.e. no collision during transmission attempts is given by:

$$P_s = e^{(-2G)} \tag{3.2}$$

In the case of LoRa nodes, $G$ depends on the TOA spent by each device and packet transmission rate $\lambda$. $\lambda$ of a packet is defined as the average frequency with which a device can transmit a packet. Figure 3.1 depicts how $P_s$ will decrease as the number of devices increases. The TOA of each device depends on its transmission configuration. Each device is assumed to have a preamble length of 8 symbols, payload length of 20 bytes and a coding rate of $4/5$. The transmission rate $\lambda$ of every node is set at 0.01s in order to adhere to the $1\%$ duty cycle limit. $G$ is thus a summation of all the nodes in the channel. As all the nodes in the channel have the same configuration, we get

$$P_s = e^{(-2 \times TOA \times N \times \lambda)} \tag{3.3}$$

If TOA or N or $\lambda$ are decreased, $G$ decreases. This results in an increase in the $P_s$.

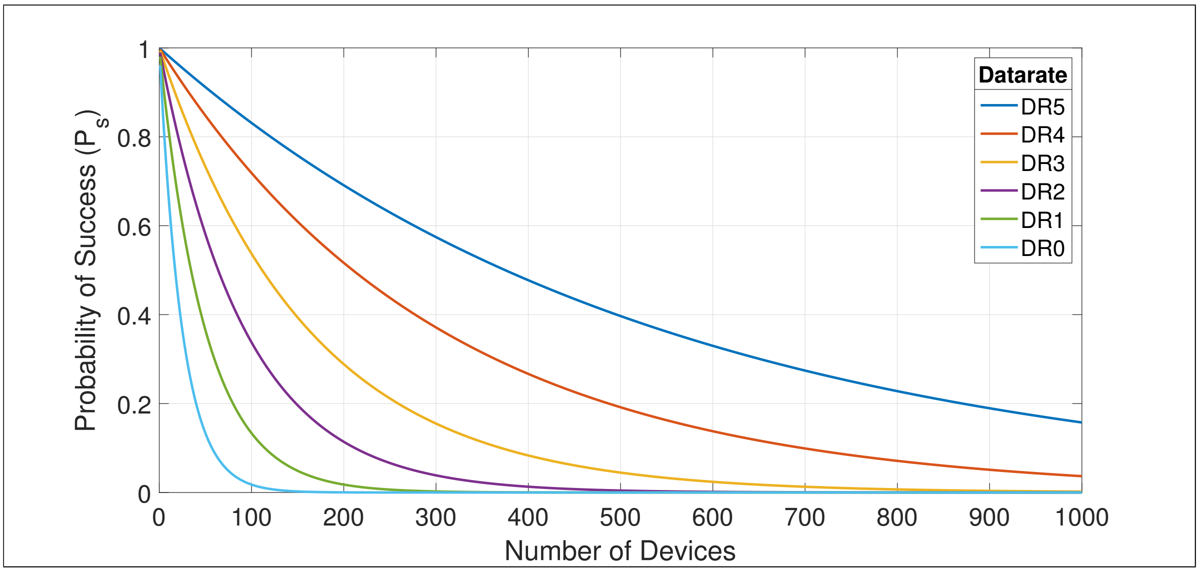



Figure 3.1: lora node behavior for different data rates

As the number of devices being serviced increases, chances of collision increase leading to a lower success rate of packets received by the gateway. This can be observed in Figure 3.1. Assuming that the probability of success must be at least 0.9, the maximum number of nodes transmitting at DR5 can be no more than 369. The numbers further decrease as the DR decreases due to increase in TOA. Figure 3.1 compares different DRs because messages at different spreading factors can be differentiated by the gateway and received simultaneously without collision. This is due to the orthogonality of the LoRa spread spectrum [14].

## 3.3. Carrier Sensing Protocols

Using carrier sensing protocols is a known option to overcome the constraints of ALOHA. CSMA devices sense the channel to check if it is busy. If so, the device waits until the end of the transmission before it transmits the packet under a specific probability called persistence. The three types of persistence algorithms in CSMA are:

- 1-persistent: When a device is ready to transmit, it first senses the channel to check if it is idle. If so, it will transmit. However, if the channel is busy the device continues sensing it until it becomes idle, and then transmits immediately.
- Non-persistent: When a device is ready to transmit, it first senses the channel to check if it is idle. If so, it will transmit. However, if the channel is busy, the device waits a random period of time before re-attempting the entire process.
- P-persistent: This access method lies between 1-persistent and non-persistent. When a device is ready to transmit, it first senses the channel to check if it is idle. If so, it will transmit. If the channel is busy it senses the channel until it becomes idle and transmits with a probability p. In the case of event 1-p, the device will not transmit but wait a random time before re-attempting the process.

Three network scenarios can be envisioned for a carrier sensing LoRaWAN as follows:

- Centralized Method
- Distributed Method
- Hybrid Method

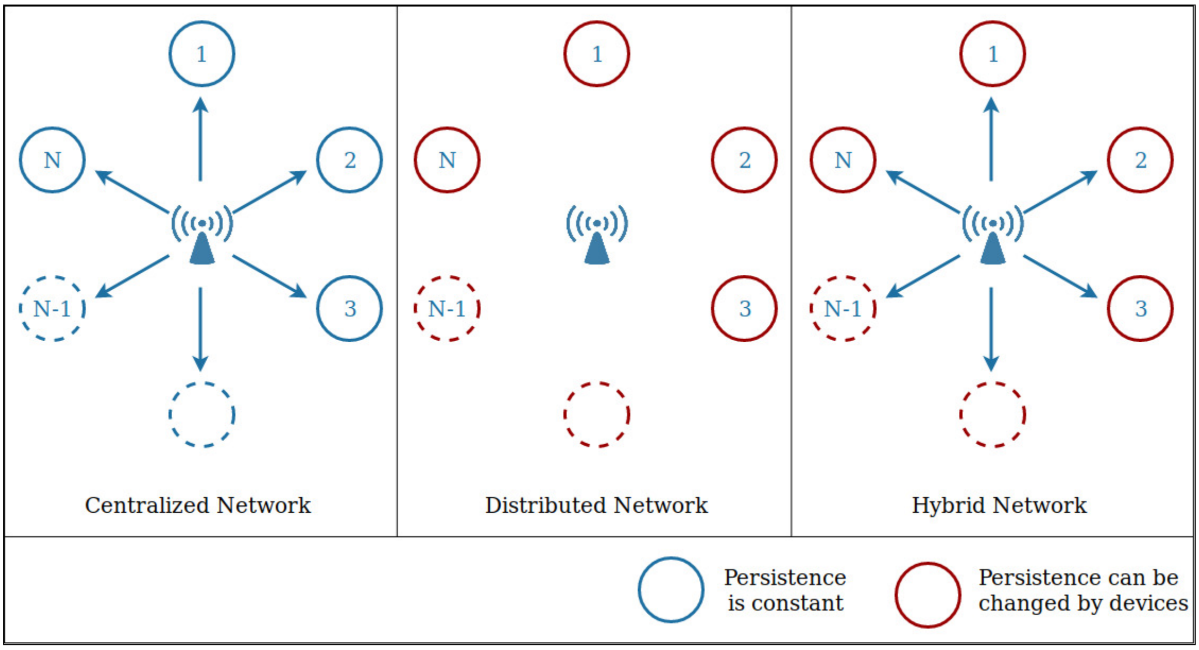



Figure 3.2: Comparison of proposed communication protocols

Figure 3.2 describes the three proposed scenarios. The centralized method relies entirely on the gateway and its ability to control the transmission rates of the devices. This protocol works without any big changes in the current functioning of LoRaWAN.

The second scenario is a completely distributed method. The end-devices will sense the channel to check if it busy or idle before transmission. The gateway does not contribute to maximizing the throughput.

A hybrid scenario is a combination of a centralized and distributed method. Here the gateway enforces an upper limit on the persistence/backoff of the end-devices. The devices are free to adjust their persistence below this enforced upper limit based on channel activity.

p-CSMA and np-CSMA protocols have been adapted and implemented in order to increase the number of supported devices in the network and to maximize the usability of the channel.

Scalability can be increased by decreasing the number of collisions in the network; given an increase in the number of serviced devices. In the case of LoRaWAN, devices are capable of performing CAD operation (discussed in Section 4.1) as a carrier sense mechanism. CAD operation is able to sense the channel and determine the data rate of the packet on the channel. As LoRa spreading factors are orthogonal, multiple simultaneous transmissions with different data rates can be decoded by the gateway. Detecting channel activity and the data rate is crucial to increase the channel throughput.

### 3.3.1. Hidden Terminal Problem

The biggest hurdle of any carrier sensing technique is the hidden terminal problem. A hidden terminal problem occurs when a device or node is in the sensing range of the gateway but not in the sensing range of some devices in the network. This causes a device to return an idle channel upon sensing, when in fact the channel is occupied. Multiple devices will then transmit simultaneously and cause a collision at the gateway.

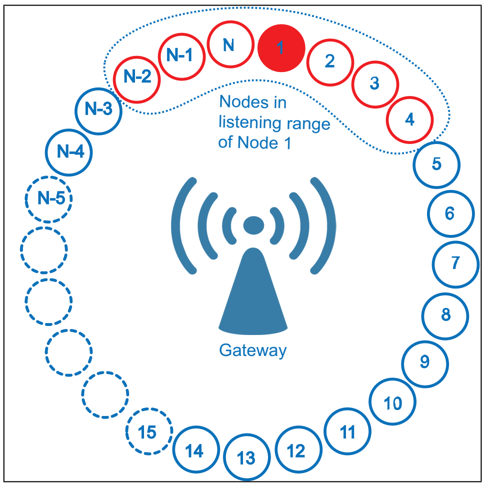



Figure 3.3: Understanding Hidden Terminal Problem

Hidden node problem exists for LoRa sensing. A LoRa device performing CAD is only able to read the energy and DR of packets within its sensing range. This concept can be better understood through Figure 3.3. For node 1, its sensing range is limited to within 4 devices surrounding it. Hence, it is unable to detect transmissions being sent by other devices outside its sensing range. Every device forms its own sensing cluster and will adjust its p-persistent or backoff value based on its surrounding nodes.

Over the years various algorithms have been adopted to solve the hidden terminal problem. Collision avoidance is done by performing a four-way handshake before transmission ([24], [25]). Another technique is the use of busy-tone transmission as proposed by Kleinrock [16]. Some hybrid techniques have been implemented which use multiple algorithms to avoid the problems of hidden terminals. None of these hidden terminal solutions are suitable for LoRa networks. [25] involves back and forth communication between end-devices and gateways which is not achievable due to long TOA of transmissions and duty cycle limits. Also, the busy-tone solution is unsuitable as the LoRa devices can transmit on multiple channels, making it difficult for them to accurately pin-point the appropriate busy channel and data rate. Using busy-tone channels for each of the transmission channel would decrease overall available bandwidth, which is counterproductive for scalability in LPWANs. This work does not attempt to solve the hidden terminal problem, but rather tries to maximize throughput in spite of it.

LoRa gateways receiving at DR0 claim to have a range of 15km in rural areas. A study by Petajajarvi et. al [26] into the coverage of LoRaWAN with respect to range and channel attenuation showed that the probability of successful reception decreased with distance and terrain. They recorded that for ground transmission 80% successful packet delivery occurred within 5 km. At sea 70% successful packet delivery was observed within 15 km. This study clearly indicates that the hidden sector in any network is subject to various factors such as interference and terrain.

### 3.3.2. Centralized Method

A centralized method is a purely gateway controlled method. The number of transmissions can be reduced by lowering the overall transmission rate in the current LoRaWAN protocol, or by implementing a carrier sensing mechanism.

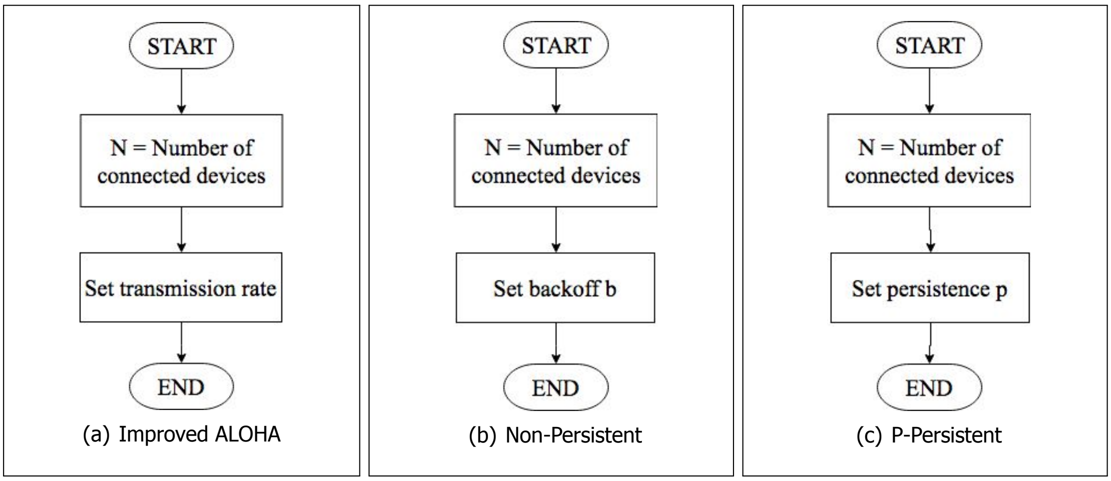



Figure 3.4: Algorithms for Centralized Method

In the first case, the gateway controls the transmission rate that all devices must adhere to. Devices follow the ALOHA like LoRaWAN protocol for transmission of packets. Transmission rate is adjusted depending on the number of devices connected to the gateway and their frequency of transmission. This limits the amount of packets transmitted per device in the network, thereby increasing the number of serviced devices. Devices will lower the transmission rate based on input from the gateway. The gateway calculates the ideal transmission rate based on connected devices using the following equation derived from Equation 3.3:

$$\lambda = \frac{log_{10}(P_s)}{-2 \times N \times TOA} \tag{3.4}$$

where,
$\lambda$ denotes the transmission rate,
$P_s$ is the expected probability of success,
N is the number of devices in the network,
TOA is the average time on air of a packet being transmitted at a certain data rate.

Here, $P_s$ is assumed to be 0.9. The gateway informs the device to follow this predetermined transmission rate at the time of joining. The algorithm can be observed in Figure 3.4(a). Even though this method will allow for a higher probability of successful transmission when number of devices is large, it inherits the drawbacks of a typical ALOHA network, restricting the network from achieving optimum throughput.

The next proposed methods use a carrier sensing mechanism. The first is a type of p-CSMA. In this algorithm the gateway dictates the persistence that all devices must follow. Intuitively, persistence must decrease as TOA or the number of devices serviced by the channel increases. This implies that persistence is inversely proportional to the number of devices and TOA. Hence, persistence p is given by:

$$p = \frac{1}{N \times TOA} \tag{3.5}$$

The algorithm can be observed in Figure 3.4(c). The devices will sense the channel and if found idle, transmit with the defined persistence p. If busy, they will backoff till the next transmission time.

In np-CSMA method the backoff value b is set by the gateway. Intuitively, the backoff factor must increase as the number of devices in the system increases. As the TOA of the devices increases the backoff factor decreases further. In persistent techniques the packets are generated by adhering to transmission rate and transmitted depending on the persistence. However, in a non-persistent algorithm the backoff value must also by dictated by the transmission rate. In a channel with less load, the LoRa nodes must adhere to the duty cycle limit of the network which defines the backoff factor. Hence, backoff factor is inversely related to number of devices, TOA and the transmission rate of each device. This backoff value b is calculated using the formula:

$$b = \frac{1}{N \times TOA \times \lambda} \tag{3.6}$$

where,
$B$ is the backoff period,
$\lambda$ is the duty cycle limit of that channel.

A device will sense the channel before transmission. If idle it will transmit a packet, else backoff for period B. The backoff period can therefore be defined as the time that the device waits before attempting to transmit a packet. Larger values of b indicate a channel with minimum number of nodes. The backoff period should be small in such a case. However, as b increases, the backoff period must increase. As LoRa devices have variable transmission parameters the best method to adjust backoff for different configurations is by considering the effect of each of these parameters, all of which are encompassed within the TOA. Hence, b and TOA are used to calculate backoff period given by the following equation:

$$B = \frac{(1 - b)}{b} \times TOA \tag{3.7}$$

The algorithm is depicted in Figure 3.4(b). The backoff value is not updated by the end-devices. This allows for the use of devices with limited computational power.

The trade-off is that the number of devices in the network is high however, the number of packets each device can transmit is decreased. This ensures that once the network has reached its optimum configuration, the total successfully received packets in the network will remain fairly constant.

A drawback of the centralized carrier sensing mechanism is that it relies solely on the gateway's ability to regulate traffic flow and optimized throughput. It gives the end-devices little control over deciding their transmission rate. It is suitable only if the devices are uniformly distributed. However, if one area is more clustered, the collisions caused in that area will be higher than those in the low traffic areas. The devices in this area will also spend more time sensing, making them less energy efficient.

In all the three methods proposed above transmission rates, p-persistence and b-backoff for devices are updated using either a JA or ADR downlink process outlined in Section 2.2.4. As the number of connected devices increases, the gateway uses ADR cycles to lower the $\lambda$, p or b values of every device.

### 3.3.3. Distributed Method

In the distributed method the devices perform carrier sensing to determine when to transmit a packet. Devices in this network follow a transmission rate limit set at 1% duty cycle. They perform unslotted p-CSMA or np-CSMA to determine if the channel is busy before transmitting a packet.

p-CSMA and np-CSMA devices are able to sense the shared medium and detect packets on the channel in order to increase the probability of a successful transmission. Figure 3.5 depicts the p-CSMA and np-CSMA protocols adopted in a distributed LoRaWAN. In the proposed p-CSMA network, the device senses the channel once it is ready to transmit. If the channel is idle, it will transmit a packet with persistence p. However, if the channel is busy the device will reschedule the transmission. It will then lower its persistence and wait till the next scheduled transmission time using the following formula:

$$p_n = p_p \times e^{-0.35 \times TOA} \tag{3.8}$$

where,
$p_n$ is the new persistence value,
$p_p$ is the previous persistence value.

Here, the $TOA$ is individually defined by the devices. Persistence value is lowered in an exponential fashion. It depends on the device's TOA and its previous persistence. The constant -0.35 has been empirically derived to gradually decrease the persistence. It allows for lowering persistence in a

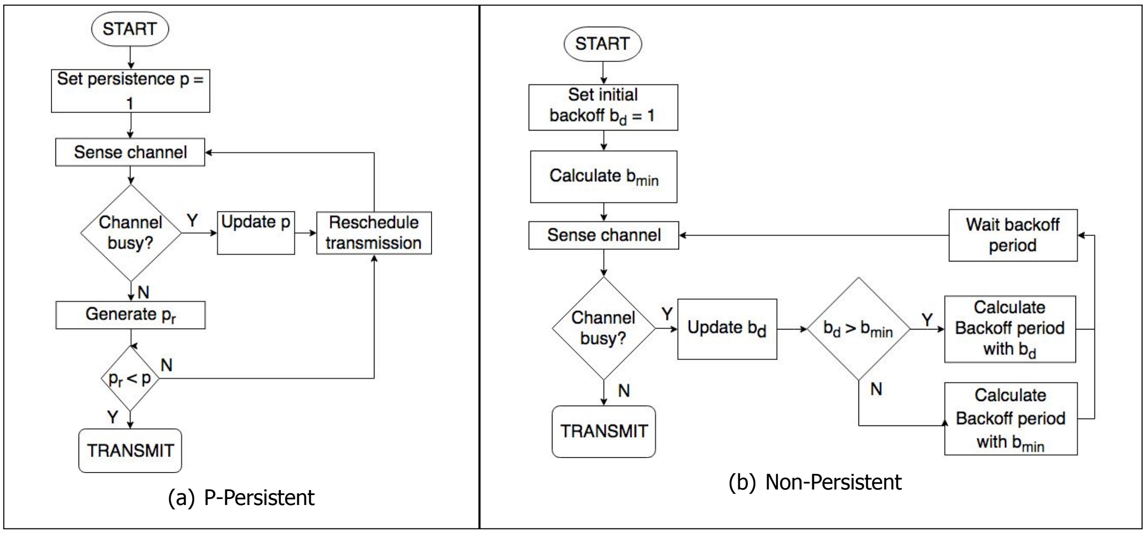



Figure 3.5: Algorithms for Distributed Method

gradual manner, to ensure that the channel is not underutilized. For a larger value of p, the persistence did not drop fast enough, which can cause collisions in the system. Figure 3.6 shows the slope with which the persistence decreases when the value for the constant is varied.

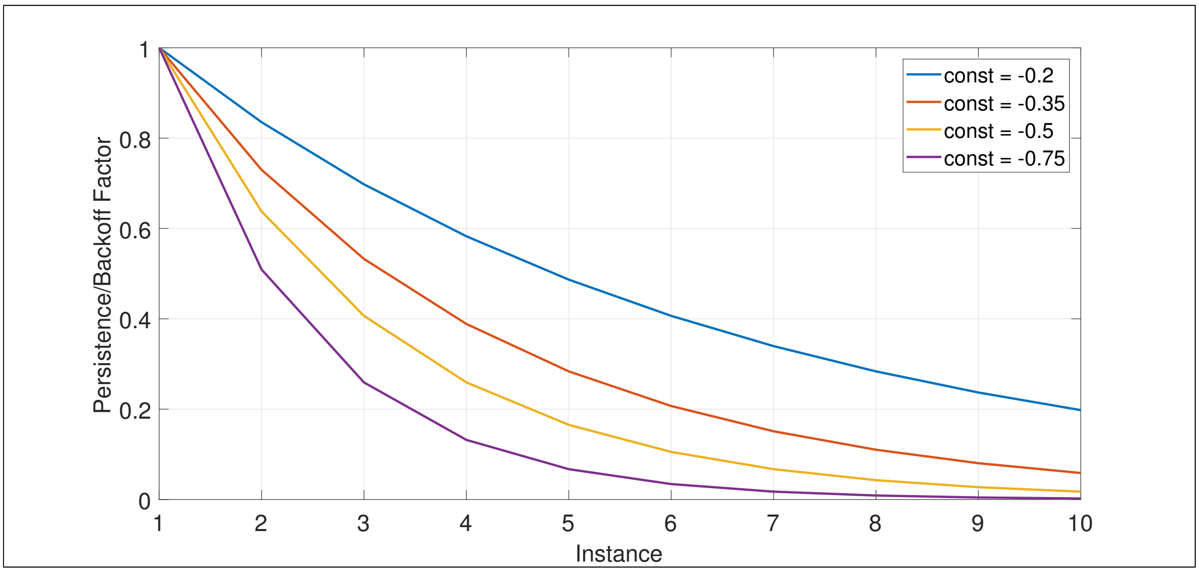



Figure 3.6: Variable values for constant

In np-CSMA protocol, the device will transmit if the channel is idle, else reschedule the transmission till the end of a certain backoff period. This backoff period changes with a value b, given by:

$$b_n = b_p \times e^{-0.35 \times TOA} \tag{3.9}$$

where,
$b_n$ is the new backoff factor,
$b_p$ is the previous backoff factor.
The backoff period B is calculated using the equation 3.7.

Again the backoff factor uses the same empirically defined slope observed in Figure 3.6 to regulate backoff factor. A distributed method relies entirely on the ability of the end-devices to sense the channel and regulate its own transmission rate. Randomly distributed devices in a high traffic cluster will adopt lower persistence values and will transmit at lower rates as compared to low traffic clusters. With an increase in the number of devices and without any input from the gateway an optimum channel throughput cannot be reached.

### 3.3.4. Hybrid Method

For the hybrid method, CSMA techniques rely on gateway and end-devices to accurately regulate transmission rate.

For hybrid p-CSMA the gateway sets the initial persistence value for every device depending on the total connected devices. It uses a JA to setup this persistence value given by equation 3.5. Devices will use this value as an upper limit. Each device performs carrier sensing before transmitting. For a busy channel, the device will reschedule the transmission, decrease p and then wait till the next scheduled transmission time. If the channel is free, it will transmit with persistence p. The total number of transmitted packets per device in the network decreases, but the probability of successful transmission increases and the energy usage is optimized.

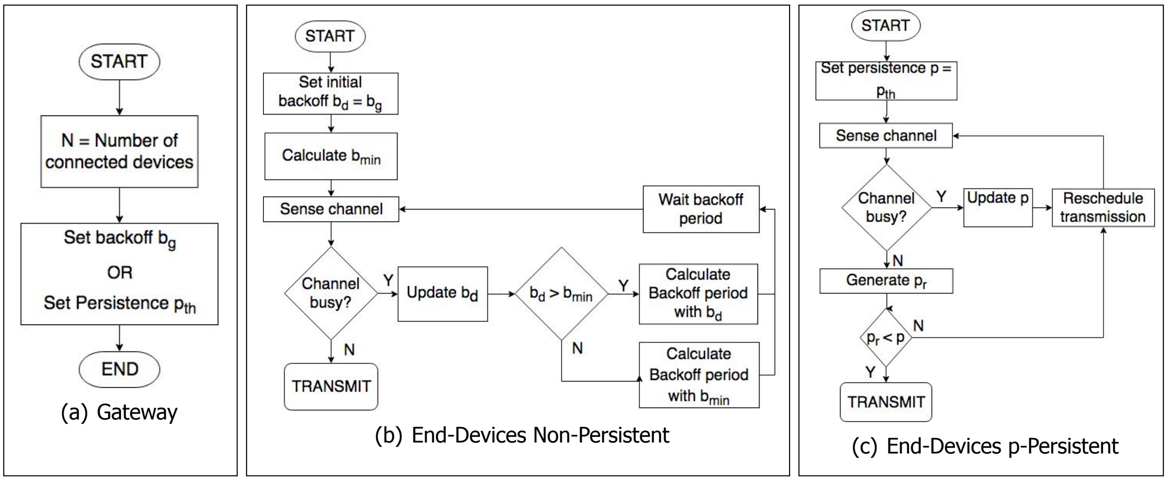



Figure 3.7: Algorithms for Hybrid Method

In the case of np-CSMA the gateway will set the original backoff value given by Equation 3.6. If devices encounter a busy channel, the backoff time is increased exponentially using Equation 3.9. If the channel is idle, transmission occurs. In order to ensure fairness, $b_n$ is only reduced till $b_{min}$ is reached. $b_{min}$ is the condition where every device will attempt to transmit at least one packet every hour. This value depends on the device's transmission rate and TOA. In the case of LoRa nodes, the transmission rate is dictated by the regional duty cycle limitations. It is hence given by:

$$b_{min} = \frac{TOA}{\lambda \times 3600} \tag{3.10}$$

Figure 3.7 depicts the algorithms followed by the gateway and end-devices when using p-CSMA or np-CSMA protocol. As the number of devices increases, the gateway will use the ADR cycles to update the persistence or backoff values.

A hybrid method is a combination of centralized and distributed methods. It can be summarized as follows:

- The gateway has a complete understanding of the number of connected devices and limits the transmission rate over the entire network.
- In a random distribution, it allows devices to adjust their persistence within their clusters, thereby reducing probability of collisions.
- For devices within a sparse distribution it limits their maximum persistence/backoff to allow devices in high traffic areas a chance to successfully deliver their packet.

The algorithms applied combine the advantages of centralized and distributed to achieve higher throughput and energy efficiency.

## 3.4. Network Stabilization Time

This section outlines the time that the network would require to reach optimal conditions when adhering to various duty cycle regulations. Two network scenarios can be envisioned where the gateway prescribes a persistence or backoff value:

- A gateway which is already at full capacity. This network is connected to the maximum number of devices that a single channel can serve.
- A gateway which has no devices connected to it. This network is empty at start.

A downlink message from the gateway must adhere to the duty cycle limits of the ISM band. This section outlines the time that a network with gateway input would require to achieve optimal throughput when adhering to duty cycle regulations. As seen in Section 3.1, the EU allows for either 0.1%, 1% or 10% on air time depending on the channel being used.

In the first case the gateway uses its entire downlink time to adjust the transmission rate or persistence of the nodes to achieve maximum throughput.

In the second case the gateway will use a percentage of its time to transmit JAs and a certain percentage to transmit persistence or backoff downlink messages. The gateway will slowly decrease the time it spends on transmitting JAs and increase the time it spends transmit persistence or backoff downlink messages.

| Configuration | Percentage of connected devices per gateway | ADR | JA | Time Required (hours) |
|---|---|---|---|---|
| 1 | 100 | 1% | 0 | 48 |
| 2 | 100 | 10% | 0 | 5 |
| 3 | 0 | 1% | 1% | 92 |
| 4 | 0 | 1% | 10% | 100 |
| 5 | 0 | 10% | 10% | 9 |

Table 3.3: Downlink Network Stabilization Time

Table 3.3 describes how many hours it takes for a network to reach optimum throughput when following a certain configuration. It 3.3 assumes that each packet transmits with DR0 and its TOA is 987.14ms. The maximum number of devices that the gateway can service in 1 hour is:

$$N = \frac{Seconds\ per\ hour}{TOA} = \frac{3600}{0.987} \approx 3646$$

A network at full capacity is hence assumed to service a maximum of 3646 devices. Configuration 1 is when a gateway is servicing maximum devices and decides to transmit downlink ADR messages while adhering to a 1% duty cycle ISM band. Configuration 5 uses a 10% duty cycle downlink frequency band. In the first iteration 10% of its time is allocated for downlink messages and 90% for downlink messages. In the subsequent iterations, 10% of JA time is allocated to downlink gradually increasing the time spent on downlink until eventually the network reaches full capacity or is stabilized at optimum throughput.

CHAPTER 4

# Carrier Activity Detection

Carrier Activity Detection or CAD mode is used by a LoRa node to make assessments about the channel state. During a CAD operation a node attempts to sense a LoRa preamble on the channel, as well as read the RSSI values present on the medium. Based on CAD preamble detection and RSSI sensing it is possible to predict the data rate of the packet on the channel.

This chapter provides insight into the inner workings of CAD and the experiments carried out in order to use it as the carrier sensing mechanism.

## 4.1. CAD Functioning

The CAD mode has two stages of sensing; radio and digital processing, each with different power consumption. The first stage is the radio function. This begins with locking the PLL. The radio needs

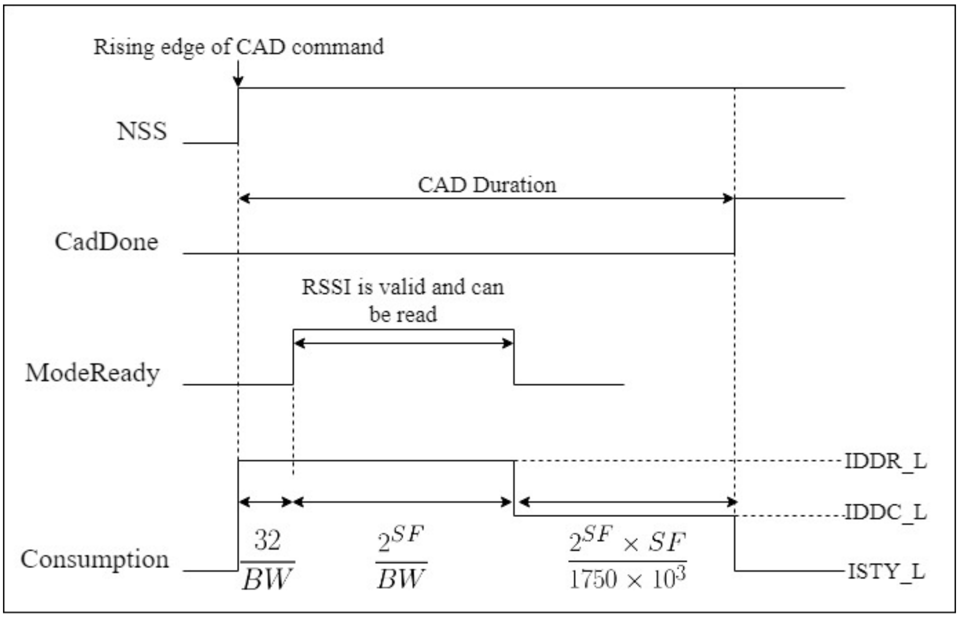



Figure 4.1: LoRa CAD Mode operation

*Source: SX1272/3/6/7/8: LoRa Modem-Low Energy Consumption Design-AN1200.17) [6]*

32 chip periods to set the ModeReady interrupt, and activate the radio receiver. The chip rate of a LoRa packet is the same as the bandwidth in chips/sec/Hz. Hence, 1 period = $\frac{1}{BW}$. After 32 chip periods, for the next $2^{SF}$ chip periods the radio is in receiver mode where it captures the LoRa preamble data from the channel. While the device is in reception mode the RSSI is sampled every 8ms and is then asymptotically analyzed. The RSSI value is calculated along the entire length of the symbol period and is directly related to the number of previously analyzed points. This makes the end of this symbol time ideal for getting the most accurate RSSI reading. The operation can be observed in Figure 4.1. The current consumed by the radio stage is denoted by IDDR_L.

The second part of the CAD operation is the digital signal processing of the data. The radio receiver and the PLL are turned off to save power and the digital processing begins. The preamble symbols are compared with the ideal LoRa preamble waveform of the radio. If the captured waveform is coherently matched to the ideal preamble waveform the CadDetected flag is set. CadDetected flag is set only if the packet on the air has the same transmission configuration as the device itself. A CadDone flag is set at the end of the waveform to denote the completion of CAD. The current consumed by the digital processing stage is denoted by IDDC_L. After the CAD cycle is complete the device will go into standby mode.

From the working of CAD it is clear that timing and energy consumption vary depending on the configuration of the nodes. These characteristics can have an effect on the sensing capabilities of the node.

## 4.2. CAD Characteristics

Timing and energy consumption are the two parameters dependent on the transmission configuration of the nodes. The energy consumption levels also vary when the chipset is changed. The values discussed below are for the SX1276 board used for experimentation in this work.

### 4.2.1. Timing

Timing of CAD loop depends on SF and BW as seen in Section 4.1. The timing of the entire loop with respect to the different data rates in the EU band is detailed in Table 4.1. Increase in BW subsequently increases the symbol rate, thereby decreasing the time for CAD.

### 4.2.2. Energy Consumption

A Semtech 1276 LoRa Radio used for experimentation requires 11.5 mA for radio operation and 6 mA for digital processing, given a bandwidth of 125 kHz. For a bandwidth of 250 kHz these values increase to 12.4 mA and 6.8 mA for radio operation and digital processing respectively. The total consumption of the device can then be computed for the different EU data rates summarized in Table 4.1.

| Data Rate | Spreading Factor | Bandwidth (kHz) | Time (ms) | | | Energy | | |
|---|---|---|---|---|---|---|---|---|
| | | | Radio | Processing | Total | Radio (IDDR_L) (mA) | Processing (IDDC_L) (mA) | Total Charge ($\mu$C) |
| 0 | 12 | 125 | 33.0 | 28.1 | 61.1 | 11.5 | 6 | 513.9 |
| 1 | 11 | 125 | 16.6 | 12.9 | 29.5 | 11.5 | 6 | 251.8 |
| 2 | 10 | 125 | 8.4 | 5.9 | 14.3 | 11.5 | 6 | 124.0 |
| 3 | 9 | 125 | 4.4 | 2.6 | 7.0 | 11.5 | 6 | 61.7 |
| 4 | 8 | 125 | 2.3 | 1.2 | 3.5 | 11.5 | 6 | 31.4 |
| 5 | 7 | 125 | 1.3 | 0.5 | 1.8 | 11.5 | 6 | 16.7 |
| 6 | 7 | 250 | 0.6 | 0.5 | 1.1 | 12.4 | 6.8 | 10.8 |

Table 4.1: CAD Time and Energy Consumption

## 4.3. CAD Detection

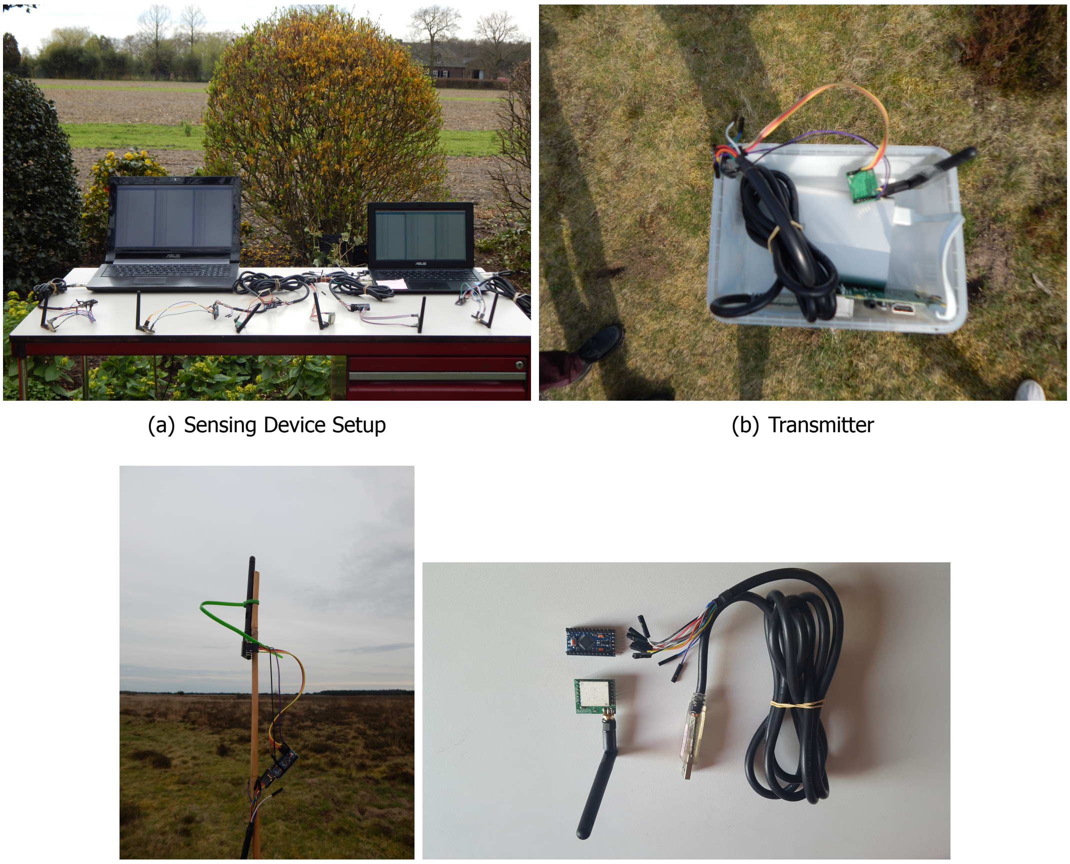
In this thesis CAD is used as the sensing mechanism to implement Carrier Sense in LoRaWAN. For accurate sensing a number of CAD attributes need to be understood. These include:

- Accuracy of Detection: The number of CAD cycles that must be performed to accurately determine the presence or absence of channel activity.
- Sensing Range of Device with respect to Detection: The range limits beyond which it becomes impossible to determine if the CADDetect value is a true or false positive.
- Sensing Range of Device with respect to RSSI: The range limits beyond which it becomes impossible to determine the presence or absence of a packet on the channel based on RSSI.

Experiments were carried out to understand the properties and limitations of each of these attributes.

### 4.3.1. Experimental Setup

The experiment carried out to test the accuracy and maximum sensing range of a device consisted of 6 sensing devices placed at a stationary Point A. The transmitter and sensing devices use SX1276 LoRa chipsets interfaced with Arduino Pro Minis. A mobile transmitter device transmitting 50 packets per data rate was used. The sensing devices were placed at a height of 1.74 m above the ground. The transmitter was mounted on a bicycle at a height of 1.5 m above the ground. The experiment was carried out in the Leenderbos/Groote Heide in the Netherlands. This area was found to be ideal as there was no interference on the channel due to the absence of any LoRaWAN coverage. Also, the terrain of this area is mostly flat which allows for minimum interference from the environment. The selected route was plotted such that the signal had minimum or no interference due to trees and other coverage. Points were selected at distances of 200 m. The experimental setup can be observed in Figure 4.2.



(a) Sensing Device Setup

(b) Transmitter

(c) Transmitter Setup

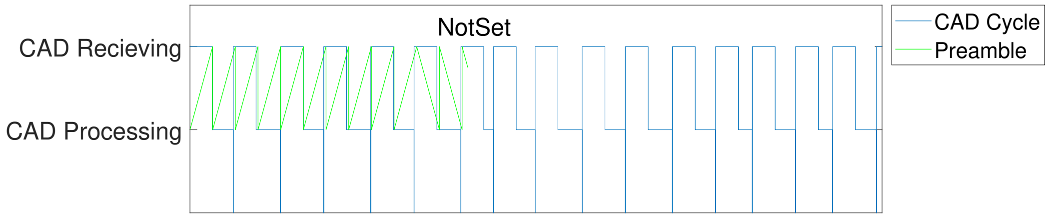
(d) Sensing Device Hardware

Figure 4.2: Experimental Setup

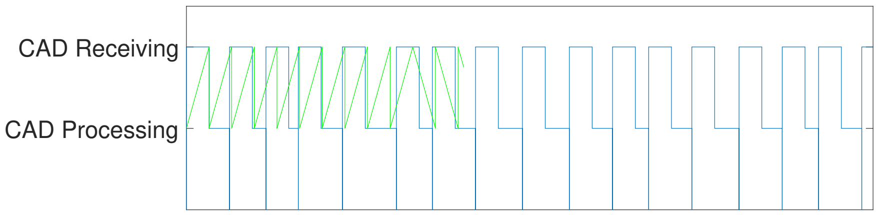
### 4.3.2. Accuracy of Detection

Accuracy of detection is defined by the number of CAD cycles that must be performed to accurately determine the presence or absence of channel activity. As seen in Section 4.1, when a CAD loop is completed, a CadDone flag is set. At the same time the CadDetected flag is set by a device when the sampled data rate sensed on the channel is the same as the data rate of the device. As observed in Table 4.1 the duration of a CAD cycle changes with the data rate being used. In the experiment outlined above, each DR0 transmission lasts for 987.14ms. The CAD duration for DR0 is 61.1ms. It is observed that multiple CAD cycles can be performed within the duration of a single transmission. The accuracy of the CadDetected flag being set depends on coherence between the captured symbols and the ideal preamble waveform.

Every CAD cycle is divided into the receive stage and processing stage. Figure 4.3 depicts two




(a) CadDetected not Set




(b) CadDetected Set

Figure 4.3: Behavior of CadDetected

cases of a captured packet. In both cases 7 CAD cycles are possible during the preamble duration of 401.1ms. Figure 4.3(a) shows that, on the $7^{th}$ CAD cycle quarter of the down-CHIRP preamble section is captured. The node is unable to accurately pinpoint whether the captured symbol is a part of the preamble and hence the CadDetected flag is not set. In the second instance Figure 4.3(b), the whole of the down-CHIRP is captured by the sensing node and correctly deciphered to be a part of the preamble. Hence, the CadDetected flag is set.

By observing the results of the above experiment it becomes clear that a single CAD cycle cannot accurately determine if the packet on the channel is using the same DR as the sensing device. Therefore, it becomes necessary to analyze the number of false negatives present in a single packet.

When sensing continuously using CAD it was observed that the entire message took 17 or 18 CAD cycles. Figure 4.5 depicts the number of false CadDetected flags set per transmission. Similarly each DR2 transmission lasts for 298.8ms. This also accounted for 17 or 18 CAD cycles when sensing at DR2. The dataset plotted in Figure4.5, also accounts for the changing distance between the transmitter and sensing device. Section 4.3.3 details the effect of changing ranges on the accuracy of detection.

### 4.3.3. Sensing Range of Device with respect to Detection

This section details the experiment and results for understanding the range limits for CAD sensing. Section 4.3.1 describes the experimental setup used to test the limits of sensing range.

Figure 4.4 describes the maximum distance for which a device was able to accurately detect the presence of another packet on the channel. It was noted that as the DR decreases, implying an increase in SF, the sensing range increases. DR0 has the longest range while DR5 has the shortest sensing range. In channel and information theory, the most difficult situation in reception is encountered when 50% of the packet is of one kind and 50% of the other. This makes it challenging to accurately pinpoint the presence of a packet beyond a certain distance. It was observed that a minimum of 3 consecutive CADDetects accurately denoted the presence of a packet on the channel. Hence, it was set as the minimum detection limit.

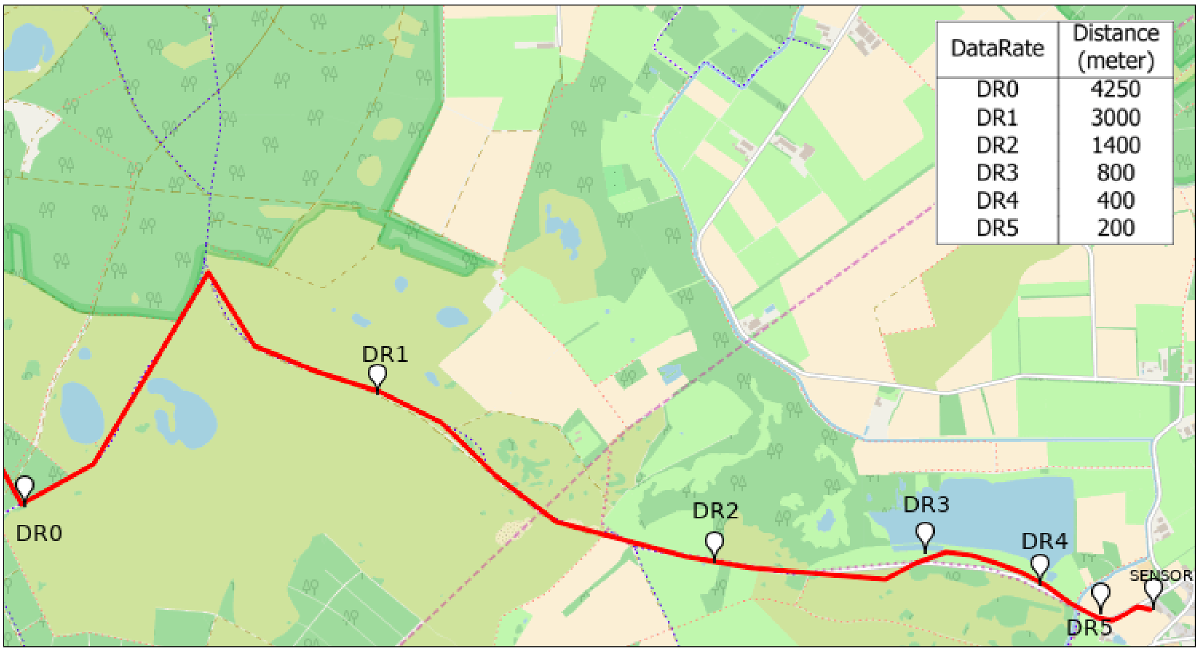
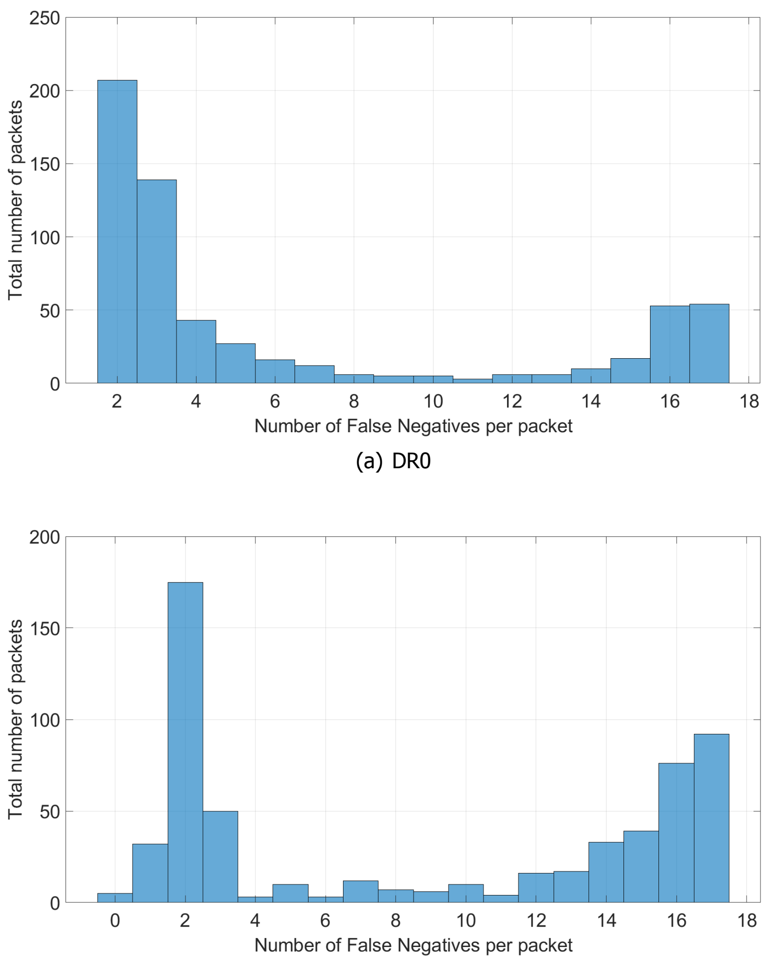



Figure 4.4: Sensing Range of End-Devices




(a) DR0

(b) DR2

Figure 4.5: Number of false detects per packet

As the distance between the transmitter and sensing device increases, the number of CadDetects per packet decreases. The number of true CadDetects decreases as the distance between the devices increases. Beyond a certain distance a device sensing at DR0 is unable to detect the presence of a packet on the channel. Figure 4.5(a) is a histogram describing the number of false negatives observed during the transmission of a packet. The x-axis represents the number of false negatives per packet and the y-axis represents the total number of packets sensed with those false negatives by the device. Figure 4.5(a) shows the receiver sensing at DR0, while in Figure 4.5(b) the receiver is sensing at DR2. The following are the observations made for DR0:

1. Approximately 350 messages were detected with 0-2 false negatives within the duration of a packet.
2. Most of these false negatives were observed at the point where the Sync Word is transmitted.
3. Beyond 1.5 km between sensing and transmitting device the false negatives within a message increased rapidly.
4. Beyond 4.25 km three positive consecutive CADDetects could not be observed. The sensing device was therefore unable to accurately decipher the data rate of the message.

Similar values were observed for the other data rates. Increase in the data rate resulted in lesser time spent in capturing and assessing the waveform leading to smaller distances of accurate detection.

### 4.3.4. Sensing Range of Device with respect to RSSI

A CAD cycle is able to capture the signal, as well as the RSSI value available on the channel. As described in Section 4.1, RSSI is sampled every 8$\mu$s and is then asymptotically analyzed while the device is in reception mode. All the captured values are used to calculate the average RSSI along the entire length of the symbol period and are directly related to the number of previously analyzed points. In order to get the most accurate reading, RSSI is read at the end of the reception window.

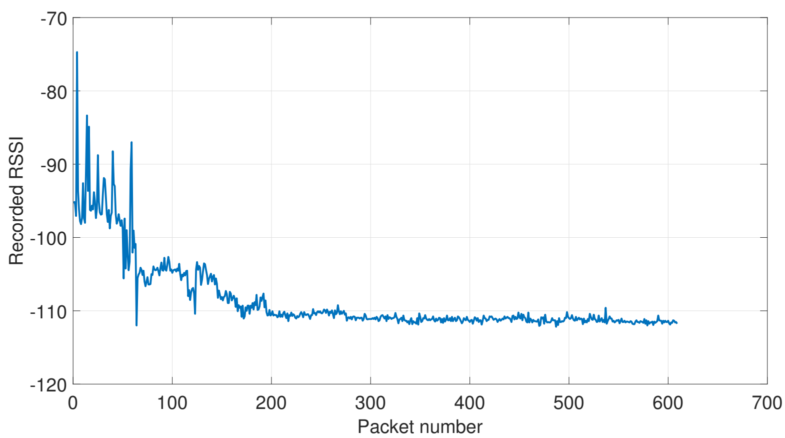



Figure 4.6: Average RSSI per packet

## 4.4. Multiple Packets

As discussed in Section 4.3.4, RSSI is not an accurate indicator of the presence of communication on the channel. Section 4.3.3 concludes that as the distance between the devices increases, the accuracy of detection decreases. But, if the devices are within LoS of each other, the RSSI detected on the channel can help to make some prediction of the number of packets simultaneously present on the channel. Depending on this value, the number of packets on the channel can also be determined to some extent. In order to test the changes in RSSI values, multiple devices were set to transmit packets on a pre-set channel.

The experimental setup consisted of a single transmitting and a single sensing device. 30 messages were transmitted per data rate. The sensing device cycled between each data rate for 30s. The RSSI and CadDetected flag values were recorded. The transmission power of the transmitting device was reduced and the experiment was repeated. The results of this experiment are detailed in Section 4.4.1. The above experiment was repeated using 2 transmitting and a single sensing device. Both devices transmitted packets simultaneously. Device 1 transmitted 30 packets per data rate, while device 2 transmitted 180 packets at DR0. The RSSI and CadDetected flag values were recorded. Figure 4.7 depicts the RSSI values when the device transmissions are simultaneous and staggered. The notable observations of the experiments are:

1. RSSI value for an idle channel lies in the range of -90 dB to -110 dB.
2. The average measured RSSI for a single packet is approximately -42 dB, irrespective of the data rate of the transmitting device.
3. The average measured RSSI when 2 packets overlap on the channel is -35 dB.
4. When using a single transmitter, changing the transmission power has little effect on the recorded RSSI value.
5. When using 2 transmitters, changing transmission powers of either has a negligible effect on RSSI values of the packet on the channel.

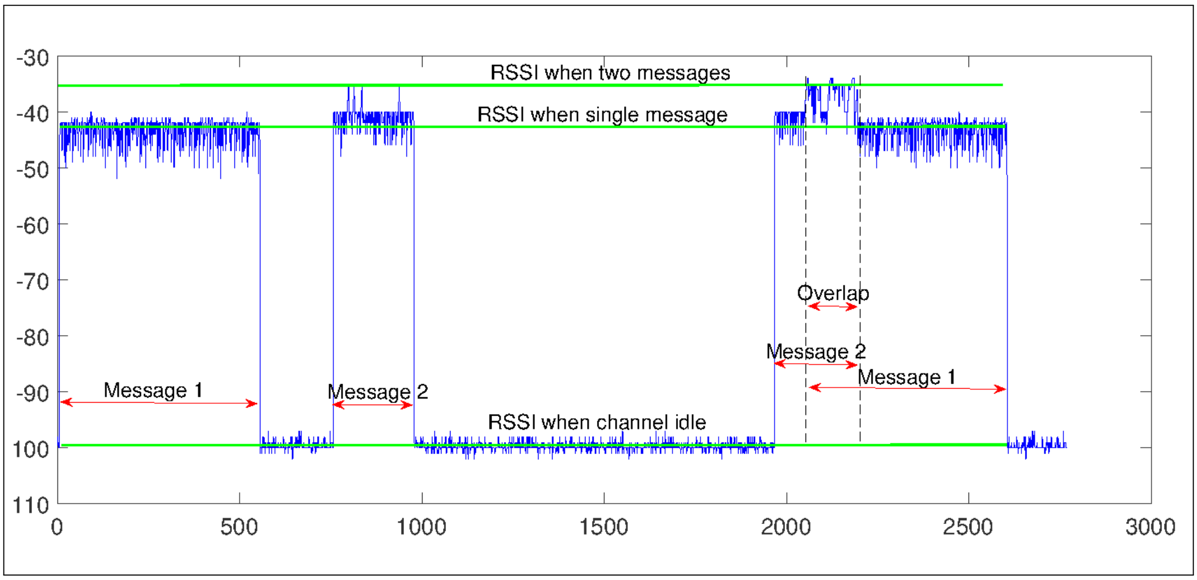



Figure 4.7: RSSI levels and behavior for single and multiple devices

### 4.4.1. Detection of Data Rate for Single Packet

The above sections explain how the combination of RSSI and CadDetected flag values can allow for reasonably accurate detection of channel activity. The CadDetected flag is set when the waveform on the channel matches the ideal preamble waveform for devices transmitting at the same data rate.

The experimental setup used to test CAD as a carrier sensing mechanism consisted of 1 device transmitting 30 packets per second. The sensing device listens on one data rate for 30 seconds before switching to the next data rate. The receiver was a SX1272MB2DAS LoRa shield running NUCLEO-L152RE Mbed chipset. The transmitter was an Arduino Pro Mini interfaced with a SX1276 LoRa chip. Based on observations made in the detection accuracy of CAD, the code had a redundancy of three positive CADDetects before accepting the data rate of the transmitter as being the same as the receiver. The devices were placed 1 meter apart and in direct LoS of each other. Therefore the RSSI value was used as a parameter in indicating channel activity.

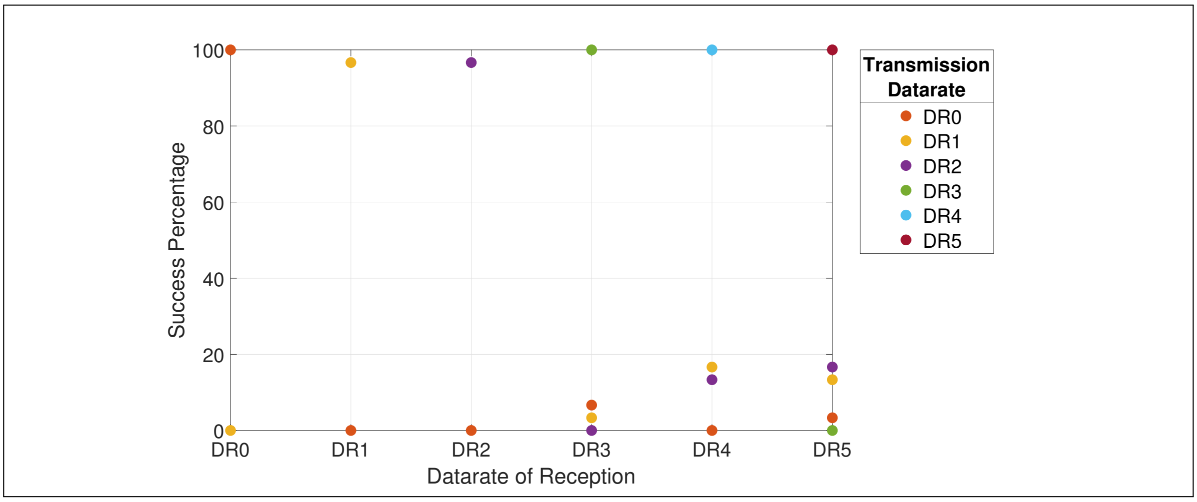



Figure 4.8: Number of packets detected successfully

Figure 4.8 illustrates the output of this experiment. The x-axis represents the different data rates of the sensing devices while the y-axis represents the probability of successful detection of the packets. The sensing devices accurately detect the presence of a packet on the channel by recognizing a change in the RSSI value. They determine if the data rate of the packet on the channel matches its own with an accuracy of at least 96%. The accuracy of detection decreases with a decrease in the SF. This can be attributed to the higher number of false detects at lower SFs. Packets transmitted at higher data rates like DR0 and DR1 are detected by the sensing device as DR4 or DR5 packets. This is an outcome of the inherent working of a CAD cycle. The duration of a CAD cycle varies with every data rate. DR5 spends only 1.3ms for capturing the waveform on the channel as compared to 33ms in DR0. The symbol time of a DR0 message is 32.7ms. A device sensing a DR5 message at DR0 will capture only a small part of the symbol, leading to an increased probability of false detection (false positive).

False detection is also possible when the sensing device does not detect the presence of a packet having the same data rate. For packets of DR2 the accurate detection percentage is observed to be 96%. However, due to falsely detected packets, the total percentage of detected packets is above 100%. The false identification of packets is attributed to the functioning of CAD loop. If sensing begins after the preamble duration of the packet, the probability that the waveform is accurately captured reduces, causing true packets to go undetected (false negative). This can be explained by the working of a CAD cycle. The device compares the captured waveform to its own ideal waveform for determining the data rate of the packet. Figure 2.2 clarifies how the waveform appears during the preamble and data transmission stages. While preamble symbols are up-CHIRPs using maximum bandwidth, the data symbols have different CHIRP values making accurate detection more difficult.

The key observations are:

1. The accuracy of detection decreases with a decrease in the SF.
2. If sensing begins after the preamble, the probability of accurate detection decreases significantly.

### 4.4.2. Detection of Data Rate for Two Packets

In a real world situation multiple packets can be present on a channel with same or differing data rates. The orthogonality property of LoRa allows for multiple packets to be received by a gateway as long as the SFs are different. For a carrier sensing LoRaWAN to be optimized it must be able to determine data rate in the presence of channel activity.

To understand how the devices behave in the presence of multiple simultaneous packets an experiment was carried out. The setup was similar to that described in Section 4.4.1. However, 2 devices were programmed to transmit simultaneously. One device transmitted 30 packets per second for each data rate, while the second transmitted a total of 180 packets at DR0. A change in the RSSI indicated the presence of multiple packets.

Figure 4.9 depicts the probability of successfully determining the data rate of packets on the channel.

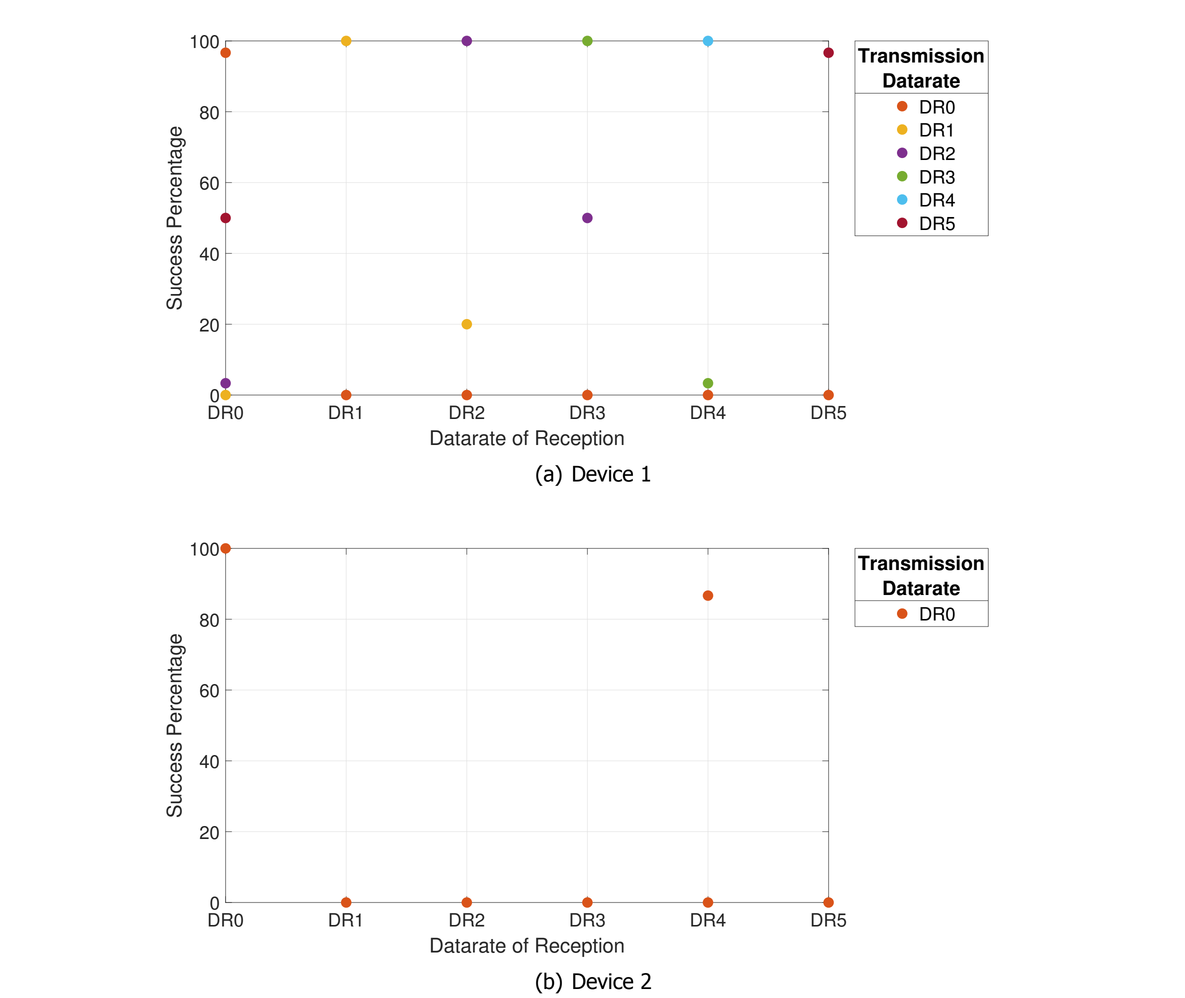



Figure 4.9: Number of packets detected successfully when sensing two simultaneous packets

The x-axis represents the different data rates of the sensing devices while the y-axis represents the probability of successful detection of the packets from device 1 and device 2. The sensing device used a combination of successful CADDetects and RSSI to determine if either of the transmissions had the same data rate as itself.

The findings showed that the sensing device was able to accurately distinguish between the data rate of messages and also determine if either of the messages had the same data rate as itself. All the packets from device 2 were accurately determined to be DR0. When sensing at DR0, the device recognized the presence of 2 packets and indicated that both were DR0 packets. For DR1 and DR2 a large number of false detects were observed on the immediate higher data rate. DR4 is one case where the device is unable to differentiate between the data rates of the two packets. This could be attributed to how the device understands the two captured overlapping waveforms. These waveforms overlap and appear at the receiver resembling the preamble of the the current sensing data rate. Figure 4.9 details the findings of this experiment. Figure 4.9(a) shows how packets from device 1 were decoded by the sensing device when programmed to listen on multiple data rates. Figure 4.9(b) depicts the decoding of packets from device 2 when sensing on different data rate. From the results we can conclude that:

1. When the devices are within LoS, the sensing device are able distinguishes between the packets and their data rate 96% of the time.

2. As the data rate increases the number of false positives increases.

## 4.5. Summary

Based on the experiments performed and documented in this chapter it can be concluded that CAD can be used as a sensing mechanism in LoRaWAN. Some of the findings have been summarized below. The results of the range experiments are specific to transmission and detection on DR0:

- 350 out of a total 900 packets transmitted at DR0 recorded between 0-2 false detects in a single packet duration.
- Most of these false negatives were observed at the point where the Sync Word is transmitted.
- Beyond 1.5 km between sensing and transmitting device using DR0 the false negatives within a message increased rapidly.
- Beyond 4.25 km for devices using DR0 three positive consecutive CADDetects could not be observed. The sensing device was therefore unable to accurately decipher the data rate of the message.
- RSSI value for an idle channel lies in the range of -90 dB to -110 dB.
- The average measured RSSI for a single packet is approximately -42 dB, irrespective of the data rate of the transmitting device.
- The average measured RSSI when 2 packets are present simultaneously on the channel is -35 dB.
- When using a single transmitter, changing the transmission power has little effect on the recorded RSSI value.
- When using 2 transmitters, changing transmission powers of either has a negligible effect on RSSI values of the packet on the channel.
- The accuracy of detection decreases with a decrease in the SF.
- If sensing begins after the preamble, the probability of accurate detection decreases significantly.
- When the devices are within LoS, the sensing device are able distinguishes between the packets and their data rate 96% of the time.
- As the data rate increases the number of false positives increases.

CHAPTER 5

# Simulation and Results

Two simulation tools were used in the course of this work to validate the algorithms proposed in Section 3.3. The first tool used was MATLAB. The hypothesis was tested in the MATLAB environment before applying it to the NS3 environment. The next sections give a brief overview and compare the results of CSMA in LoRaWAN.

CAD is applied as the carrier sensing technique in this work. The observations regarding the functioning of CAD were modelled into the sensing algorithm used for the simulations. The results from Chapter 4 lead to three major characteristics of the sensing mechanism implemented in the simulators. They are as follows:

- Three positive CADDetects must be registered to accurately determine the data rate of the packet on the channel. This means that a device performs 3 CAD cycles per channel sense before deciding if the channel is idle or busy.
- RSSI is not used as a measure of channel activity.
- CAD detection range of the devices is defined by the range experiments in Section 4.3.3.

## 5.1. MATLAB

The algorithms explained in Section 3.3 were modelled in MATLAB in an event driven fashion. The proposed ALOHA, p-CSMA and np-CSMA were applied to the three network conditions: Centralized, Distributed and Hybrid. The results from each were then compared and analyzed. For the sake of simulation and experimentation the following assumptions have been made:

- Devices are uniformly distributed around the gateway.
- Payload of the nodes is always set to 35 bytes.
- The hidden sector is $\frac{4}{5}$.

### 5.1.1. Hidden Node Problem

Hidden node problem is experienced by devices attempting to setup CSMA protocols. LoRa devices are subject to duty cycle limitations and path-loss. Figure 5.1 details the throughput of devices when the hidden sector changes in np-CSMA protocol. All devices are assumed to be transmitting at DR1 with a backoff factor of 0.027. That means every device will only try to transmit 1 packet per hour. As the hidden sector increases, the throughput decreases. The collisions increase as the number of devices within the detection range decreases. This causes devices to transmit simultaneously causing collisions.
Key takeaways:

1. The throughput of np-CSMA implementation is 0.43 when no hidden sectors exist.
2. The throughput increases steadily up to 2000 devices as the network is able to successfully allocate space for every packet. Beyond 2000 devices some packets will not be transmitted and hence the throughput remains constant.

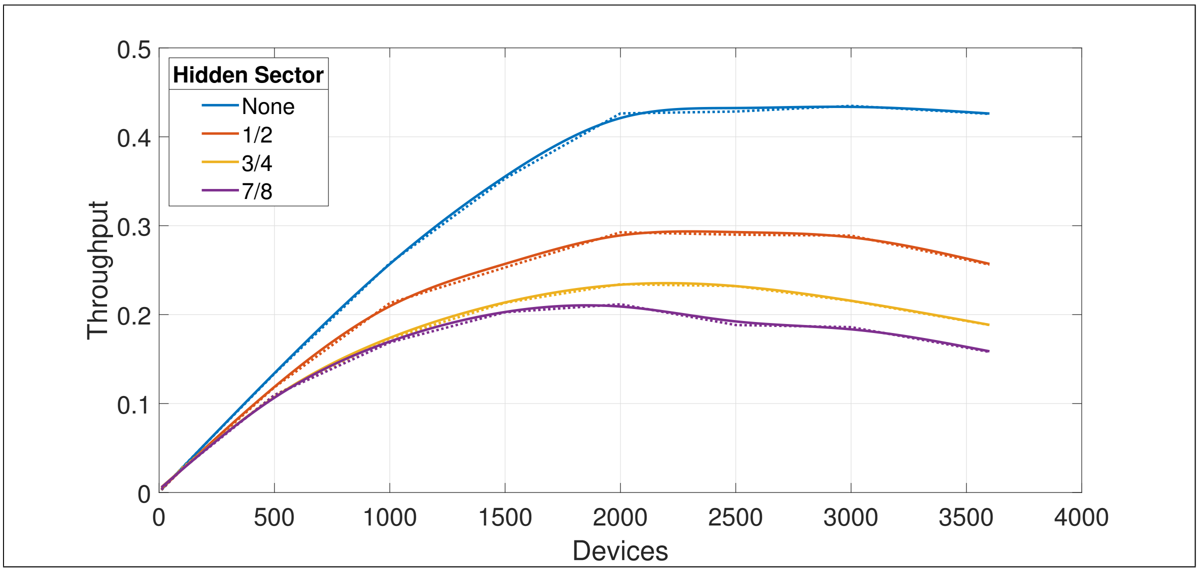



Figure 5.1: Throughput when devices and hidden sectors vary

3. Increase in the hidden sector results in a subsequent decrease in the throughput of the channel. The factor with which throughput decreases gets smaller as the hidden sector increases.

To closely mirror a real world situation a hidden sector of $\frac{4}{5}$ was assumed. This ratio depends on the area of the network outside the sensing range of the device versus the entire area of the network. For a network transmitting at DR1 the gateway range is 7 km. The sensing range of a DR1 device is 3 km. In a uniform distribution, this amounts to $300^{\circ}$ out of $360^{\circ}$ being out of sensing range of the device, which approximately equals a hidden sector of $\frac{4}{5}$.

### 5.1.2. Centralized Method

This section details the simulation results of the proposed algorithms in Section 3.3.2. Here, the network is entirely gateway controlled. In the case of CSMA protocols the devices only perform carrier sensing and do not update persistence or backoff values.

#### Variable Transmission Rate

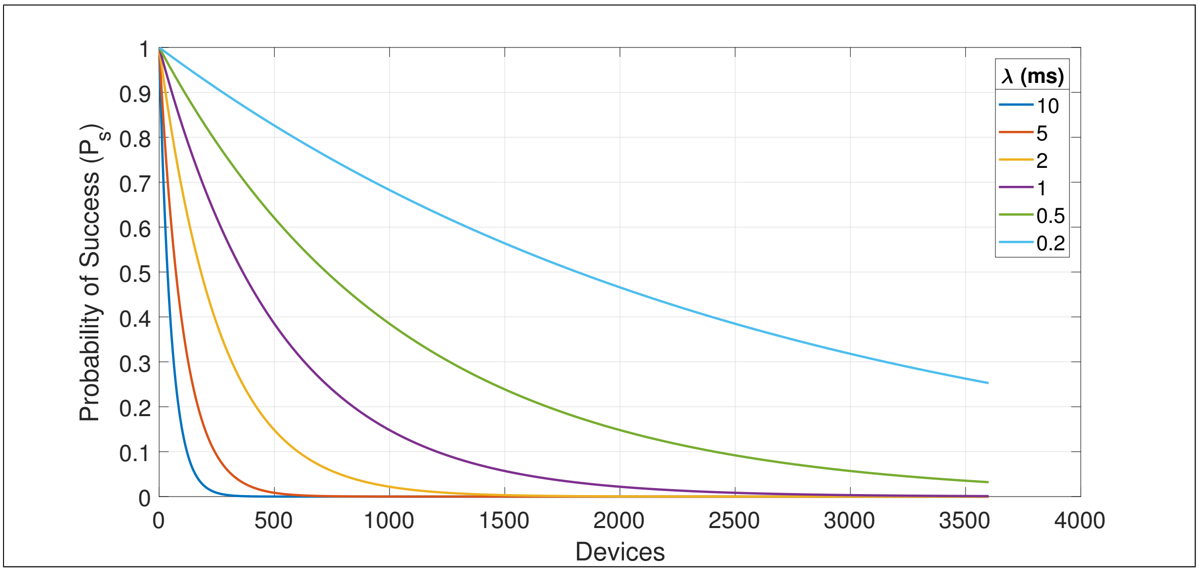



Figure 5.2: Variable transmission rate

The devices transmit with the ALOHA like LoRaWAN protocol. Figure 5.2 assumes that each packet transmits with DR1 and its TOA is 987.14ms. The maximum number of devices that the gateway can service in 1 hour is:

$$N = \frac{Seconds\ per\ hour}{TOA} = \frac{3600}{0.987} \approx 3646$$

Minimum transmission rate assumes that every device attempts to transmit one packet per hour. In this simulation it is given by $\frac{1}{N}$ and is equal to 0.2ms. At this rate, a maximum of 250 devices are supported, while maintaining the $P_s$ at 0.9. As the transmission rate is lowered, probability of successful packet delivery increases due to fewer packets being transmitted per device.

Figure 5.2 details how many devices can be supported by a gateway when transmission rates are varied between duty cycle limit to a minimum transmission rate. It is impractical to go beyond the minimum transmission rate as it is assumed that the devices will attempt to transmit at least one packet per hour to ensure fairness.

### Persistent CSMA

Figure 5.3 details the output when persistence is varied in a p-CSMA network. A uniform distribution of devices is assumed around the gateway. The devices transmit at DR1 with a TOA of 987.14ms. The throughput of the network depends on the number of successfully received packets $N_{sp}$. The normalized throughput for an hour is the ratio of the number of successful packets times their individual Time on Air. The TOA being in seconds the throughput equation is as follows:

$$S = \frac{N_{sp} * TOA}{3600} \tag{5.1}$$

The dotted lines in Figure 5.3 denote the actual throughput, while the solid lines give the generalized

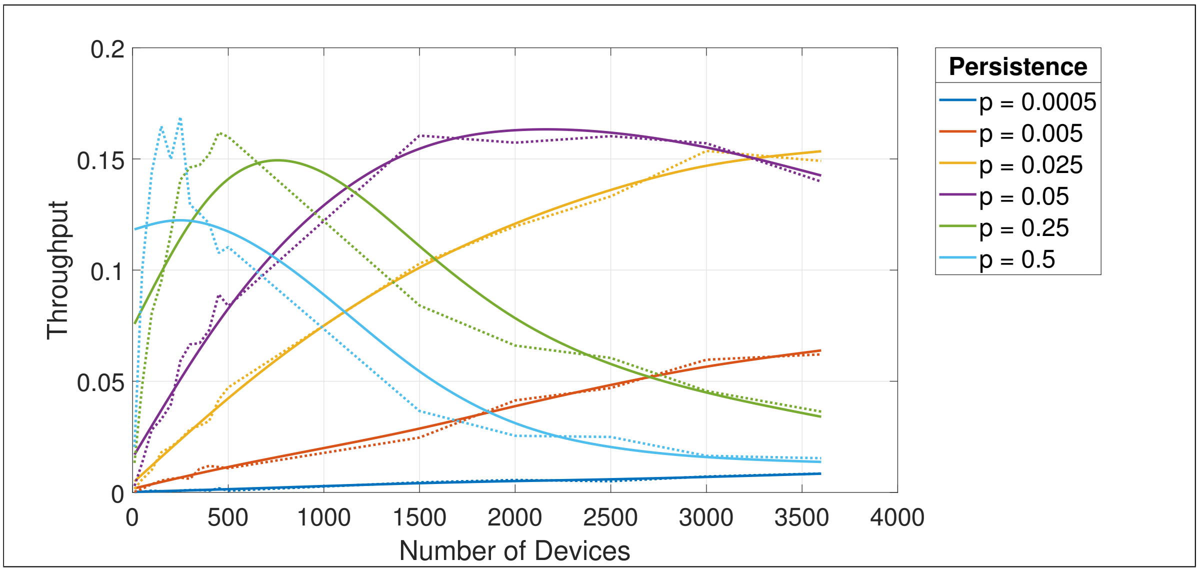



Figure 5.3: Throughput for gateway controlled p-CSMA

behavior at each persistence. Packets are transmitted with a persistence p when the channel is idle. The maximum throughput varies depending on the persistence. The above configuration gives the highest overall throughput at persistence p equals 0.05. For lower values the throughput drops quickly as the number of devices increases. For higher persistence values, not enough packets are generated in the network. For larger number of devices, maximum throughput is reached at lower persistence values. For all cases the maximum throughput does not exceed 0.18. Hidden sector causes collisions in the network reducing the overall throughput.

### Non-persistent CSMA

Figure 5.4 details the throughput of devices when the backoff factor varies in np-CSMA. The network consists of devices transmitting at DR1 with a payload of 35 bytes. The TOA of these devices is

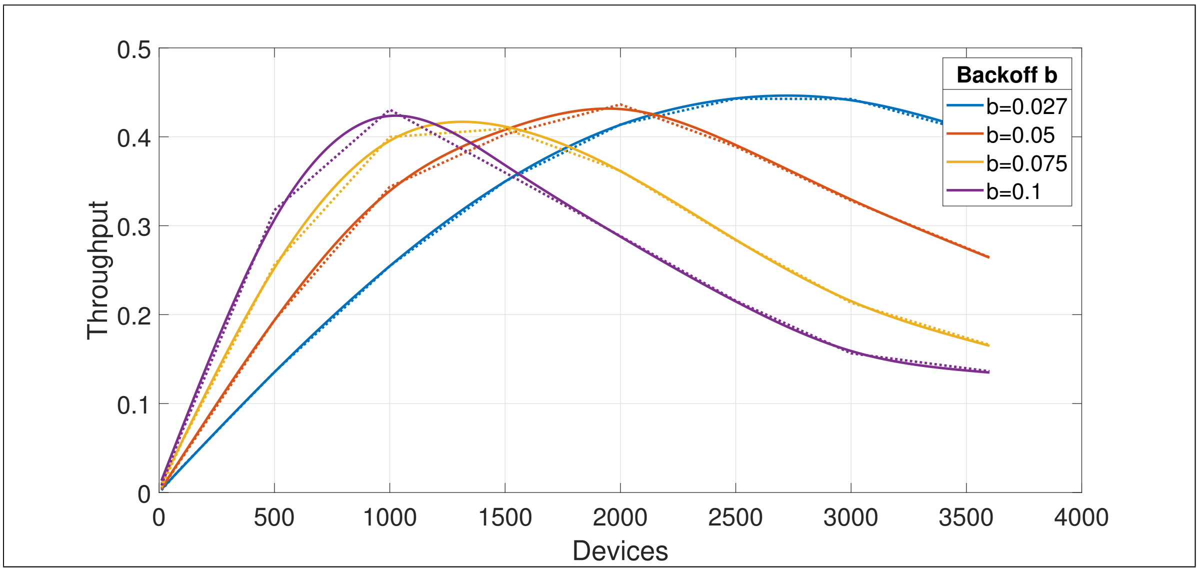



Figure 5.4: Throughput when devices and backoff values vary

987.14ms. As observed in Equation 5.1.2 it is clear that the total DR1 packets serviced by a single gateway in one hour cannot exceed 3646. To allow for at least one transmission per device the backoff for this scenario cannot be less than 0.027. The backoff factor is calculated using equation 3.6 by the gateway. As the backoff factor increases, the number of packets transmitted per device decreases. However, the number of collisions also decreases. The throughput is limited by the number of successfully received packets and the hidden sector.
Key takeaways:

1. For the centralized controlled ALOHA, as the transmission rate is lowered the probability of successful packet delivery increases due to fewer packets being transmitted per device.
2. Lowest transmission rate is given by $\frac{1}{N}$ and is equal to 0.2ms. At this rate, a maximum of 250 devices are supported, while maintaining the $P_s$ at 0.9.
3. In p-CSMA the maximum throughput varies depending on the persistence and number of connected devices. For larger numbers of devices, maximum throughput is reached at lower persistence values.
4. In np-CSMA, a decrease in backoff factor results in a decrease in the number of packets transmitted per device. However the number of collisions also decreases. The throughput is limited by the number of successfully received packets and the hidden sector.

### 5.1.3. Distributed Method

This section details the simulation results of the proposed algorithms in Section 3.3.3. A distributed network can be envisioned as a centralized network with gateway persistence or backoff set to 1.

#### Persistent CSMA

In p-CSMA, persistance is used to determine the number of packets that will be transmitted by the device. For lower persistance values the number of packets sent by a device will be low. As persistance increases the number of packets transmitted per device increases, thereby increasing the total packets in the network. The devices adjust persistence within their cluster, but are unable to understand the overall network distribution without input from the gateway. For fewer devices the channel is underutilized. As the number of devices increases, the network is susceptible to a higher collision rate, decreasing the overall throughput.

Figure 5.5 details the throughput as the number of devices increases while the initial persistence remains constant. Even though the devices are able to adjust their persistence within their clusters, this method proves to by sub-optimal and the throughput drops exponentially.

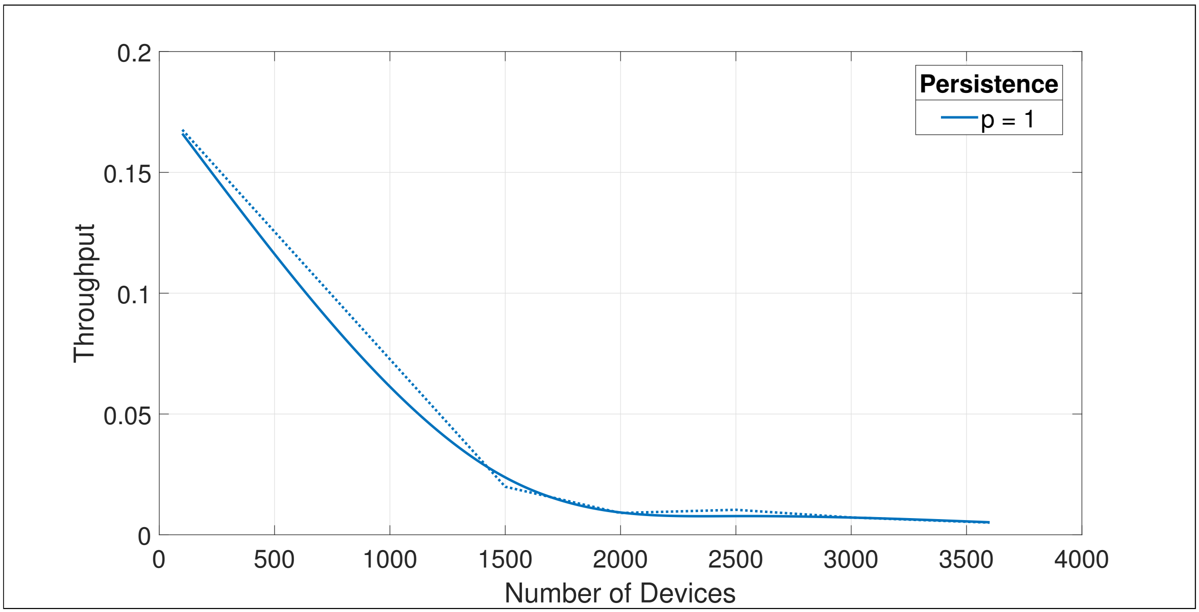



Figure 5.5: Throughput when devices and persistence values vary

Non-Persistent CSMA

The throughput in np-CSMA in a distributed network has the initial backoff value b set to 1. As the density of nodes increases, the value of b will be lowered by the devices. This is the main difference between a centralized 'b equals 1' np-CSMA network and the distributed np-CSMA. This results in under utilization of channel at lower density of devices and higher collisions as the number of devices increase.

A distributed network can only be advantageous in a controlled environment where the prescribed persistence or backoff is input into the device at the time of initialization. After that, the gateway will not send any downlink packets to regulate p or b. Hence, it becomes impossible to optimize the throughput if the number of devices changes.

Figure 5.6 describes the throughput when backoff factor is set to one. The throughput is constant

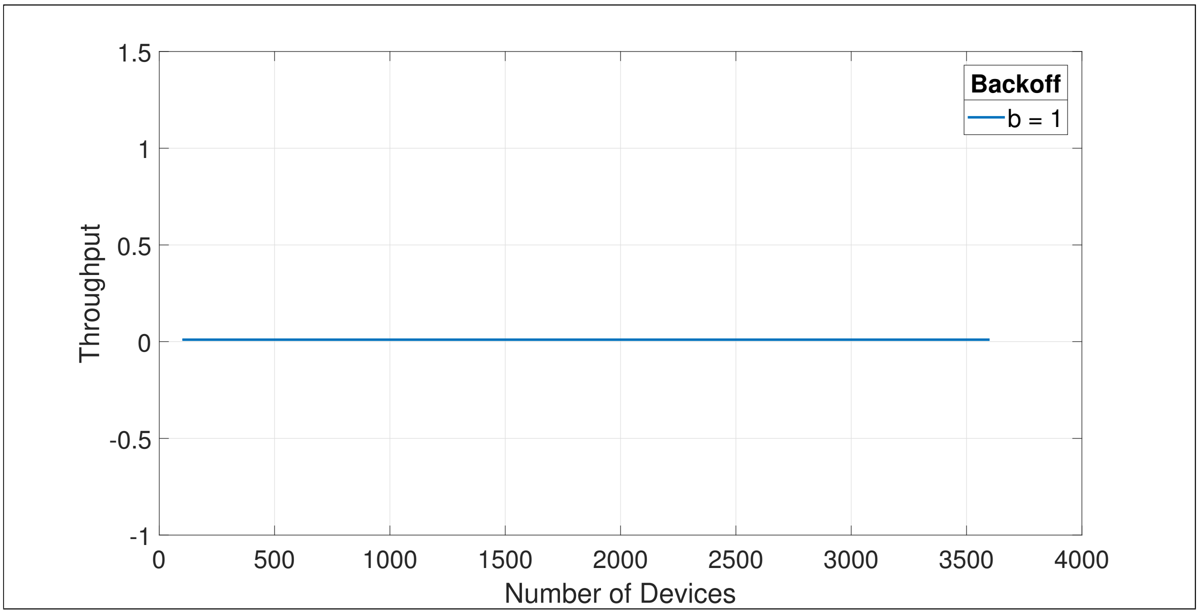



Figure 5.6: Throughput when devices and backoff values vary

as only a maximum of 39 packets are able to be successfully delivered at the gateway. The minimum number of devices for this simulation was set at 100 devices. This implies, that distributed backoff cannot increase the throughput of the systems. Key takeaways:

1. The devices are unable to understand the overall network distribution.
2. For fewer devices the channel is underutilized.
3. As the number of devices increases, the network is susceptible to a higher collision rate, decreasing the overall throughput.

### 5.1.4. Hybrid Method

This section details the simulation results of the proposed algorithms in Section 3.3.4. The hybrid protocols combine the centralized and distributed algorithms to optimize the output. For p-CSMA and np-CSMA the upper threshold values are set by the gateway, but the devices also update their internal persistence and backoff values.

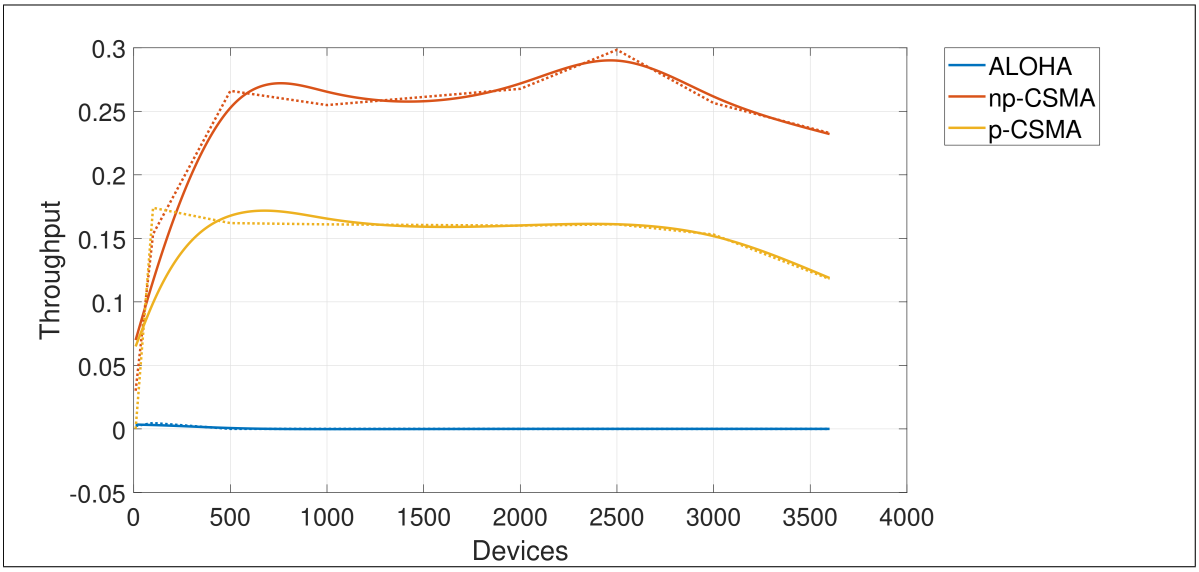



Figure 5.7: Comparison of ALOHA versus Hybrid Sensing Protocol

Figure 5.7 compares the network throughput when using the ALOHA protocol versus the hybrid protocol in np-CSMA and p-CSMA. The hidden sector is assumed to be $\frac{4}{5}$. A DR1 with 35 bytes payload transmission configuration is used. A maximum of 3646 devices can be serviced by the network as seen in Equation 5.1.2.

For ALOHA the packets are transmitted once they are generated, with a 1% duty cycle limited transmission rate of 0.01s. The number of successful packets for ALOHA is calculated by multiplying $P_s$ obtained from Equation 3.3 with the total number of packets generated by the devices. The throughput can then be derived by using Equation 5.1. As observed from Figure 5.7 the throughput of ALOHA is lower than the CSMA algorithms.

#### Persistent CSMA

For the hybrid p-CSMA the p value changes with the number of devices. As the number of connected devices in the network increases, the persistence is dropped. The highest throughput is observed when the number of devices in the network is 650 and the persistence is 0.1. Beyond this the throughput remains stable around the 0.16 mark. At 3000 devices the throughput begins to decrease. At 3500 devices the throughput drops to 0.11. Here the optimum persistence is 0.01. Out of the total generated packets only 658 are transmitted of which 433 are successfully received. Beyond this point, if persistence is lowered, fewer packets are transmitted. This causes an increase in the probability of successful transmission, but lowers the overall transmitted packets and therefore received packets, which results in the decrease of the normalized throughput. Throughput is also lowered due to collisions caused by the devices in the hidden sector.

Non-Persistent CSMA

In the case of np-CSMA hybrid protocol the backoff values are updated. When the number of devices is less than 100, b is set at 1. As the number of devices increases the gateway updates the backoff factor using Equation 3.6. Beyond 2000 devices b is set to 0.027, which is the minimum backoff factor. At 2500 devices the stretching point of the np-CSMA network is reached. As the number of devices trying to transmit a packet increases further, the probability of collision increases rapidly, decreasing the throughput. Beyond 2500 devices at b equals 0.027 in np-CSMA a device may not transmit even a single packet per hour. The second factor contributing to lowered throughput is the presence of hidden sector. When devices are beyond sensing range of each other, they can believe the channel to be free and cause collisions in the system. The highest throughput is observed when 2500 devices are transmitting a maximum of 1 packet each.

Key takeaways:

1. For p-CSMA at 3000 devices the throughput begins to decrease. At 3500 packets the throughput drops to 0.11. Here the optimum persistence for the given configuration is 0.01.
2. If persistence is lowered, fewer packets are transmitted resulting in an increase in the probability of successful transmission.
3. At 2500 devices in np-CSMA the stretching point of the np-CSMA network is reached. As the number of devices trying to transmit a packet increases further, the probability of collision increases rapidly decreasing the throughput.

## 5.2. NS3

NS3 is a discrete event-driven network simulator used to simulate a wired or wireless network. It runs on a C++ and python base. In this work NS3 is used to test how a LoRa network will act when deployed with the carrier sensing protocol

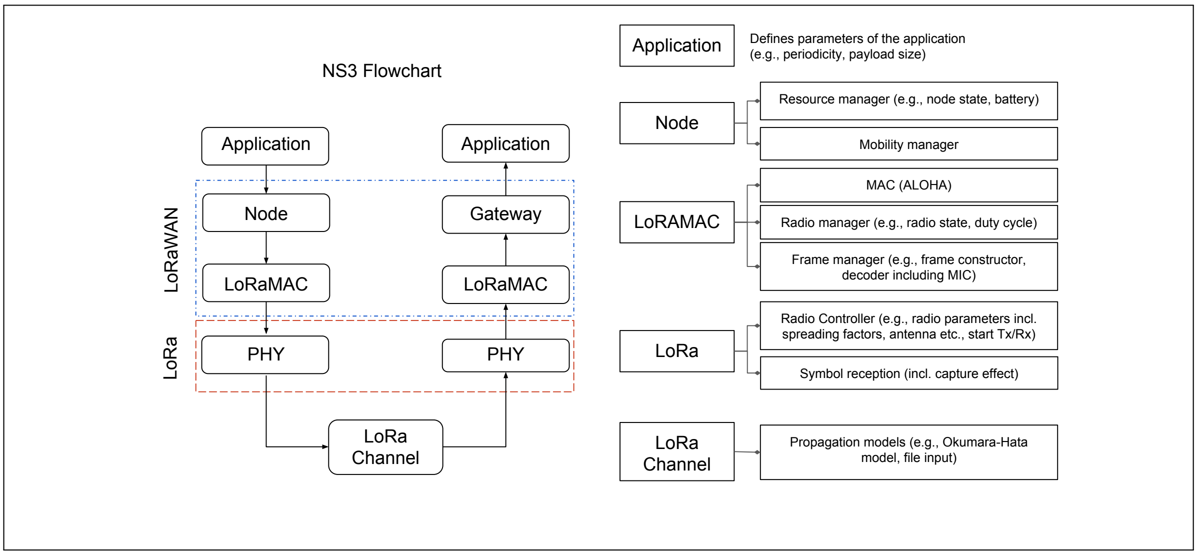



Figure 5.8: LoRa NS3 Block Diagram

### 5.2.1. NS3 structure

Any NS3 simulation is divided into 5 parts:

- Topology definition: The physical layer and characteristics of the network are defined. The helper functions are defined in this field. The PHY properties of LoRa are defined.
- Model development: The type of communication being used. The LoRaWAN protocol model is added to the simulation.

- Node and link configuration: The individual characteristics of nodes and gateways are initialized.
- Execution: The simulation is run at this point and the appropriate logs are created.
- Graphical Visualization: All the raw or processed data can be run through visual aids to better understand the simulated network.

Figure 5.8 depicts the block diagram of the developed NS3 module. The application layer defines parameters such as payload size and periodicity of transmission. The node characteristics such as battery capacity, persistence, transmission parameters are implemented. The LoRaMAC manages the radio state, duty cycle limitations and all MAC communication. The LoRa PHY is where the actual transmission parameters such as SF, BW and CR affect the message transmission. Qualities like capture effect and resistance interference become a factor here. The bottom-most layer is the LoRa channel which deals with channel attenuation and modelling.

### 5.2.2. Structure of code

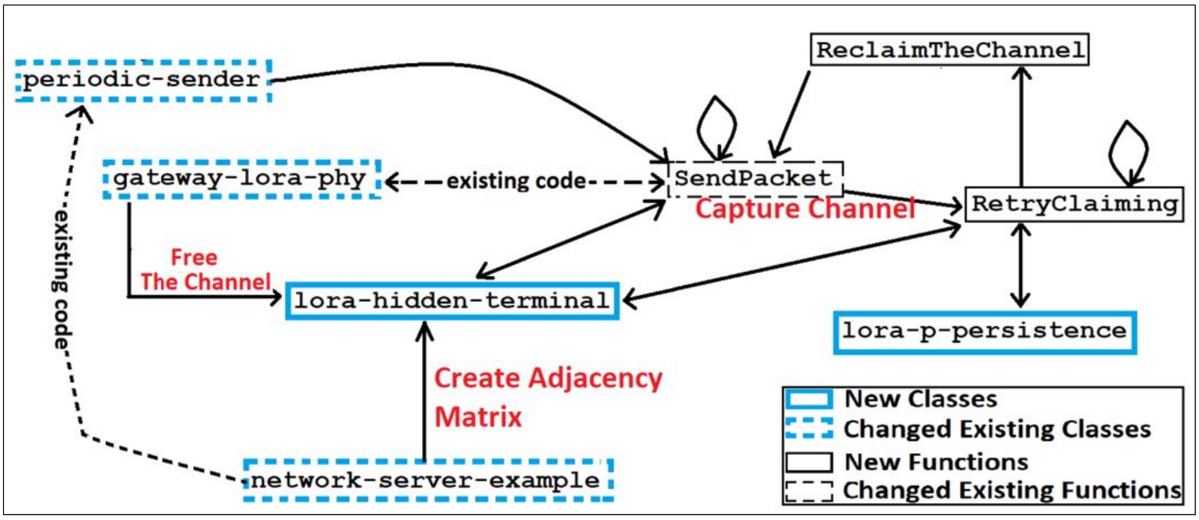



Figure 5.9: High-level structure of NS3 framework[27]

The NS3 implementation of LoRaWAN used is built by Kouvelas et al. [27] which in turn is based on the work of Magrin et al. [28] and [29]. In order to implement p-CSMA various classes were added by [27] to the original LoRaWAN simulation. They are as follows:

- Network Server Example: This is the backbone of the simulation. Values such as fading path, number of devices and MAC/PHY characteristics are defined here.
- Periodic Sender: Originally LoRaWAN transmission is controlled by the defined periodicity and duty cycle limitation of the device. When p-CSMA is to be applied the number of transmissions also depends on the persistence value. This class controls if the device will try to claim a channel to transmit a packet.
- LoRa Hidden Terminal: Due to limitations of CAD, the sensing range of devices leads to the hidden terminal problem. This class creates an adjacency matrix at the start of simulation to define which devices are within listening range of each other. It interacts with the function SendPacket to decide if an end-device will try to claim the channel for transmission.
- LoRa p-persistence: This class allows for setting of persistence values for end-devices. It also dictates if transmission occurs in a persistent fashion by using a rand function.
- Gateway LoRa Phy: The channel state is updated depending on if the packet is received. Orthogonality, RSSI and collision are tested to determine if the packet is received.

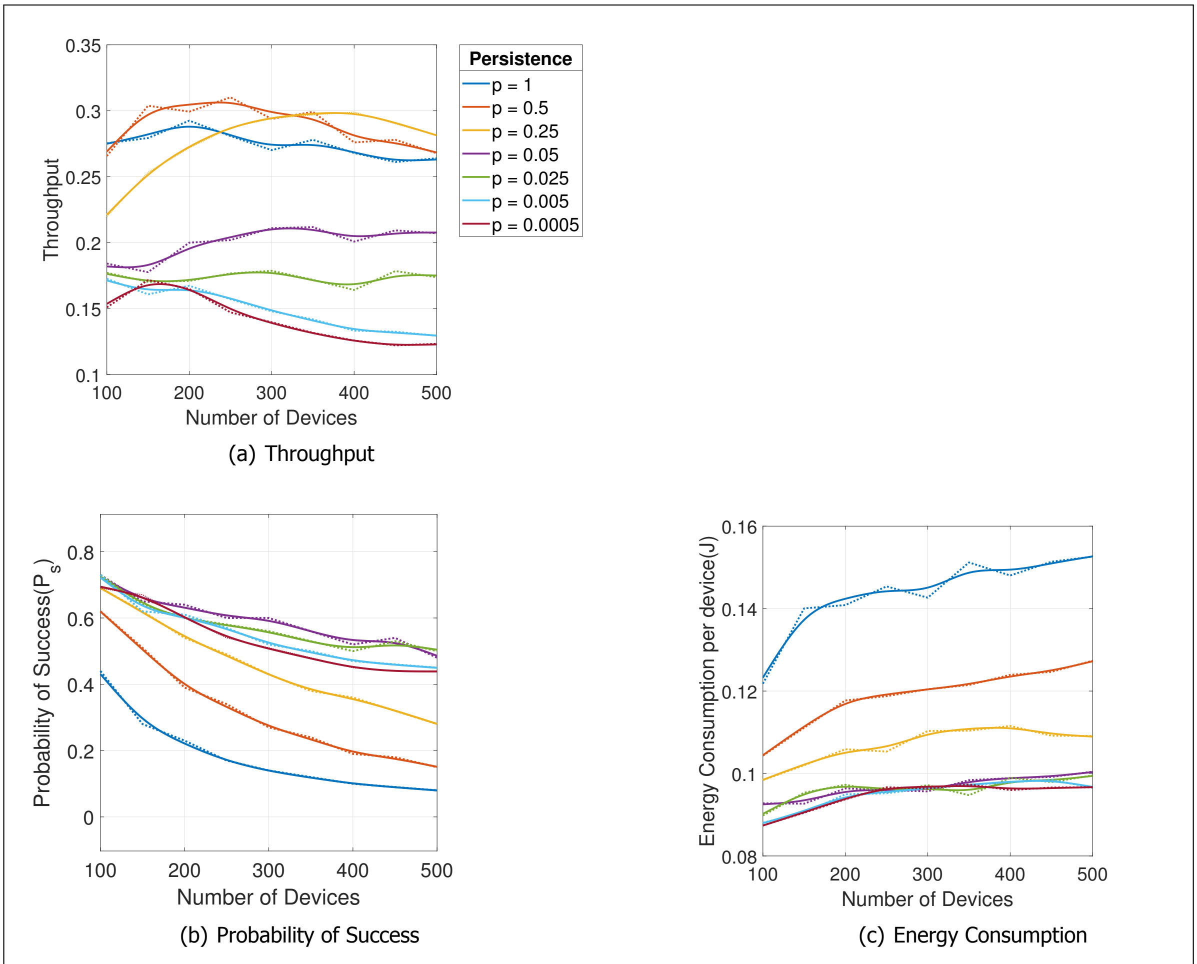
An overview of the functioning of the NS3 simulation is presented in Figure 5.9. The new classes enable p-CSMA as a MAC layer protocol and incorporate conditions like hidden terminals, SNR limits, etc.

## 5.3. NS3 Results

The NS3 setup was similar to the MATLAB setup. The devices were distributed around the gateway uniformly. The proposed persistent algorithms were tested using a variable number of DR1 devices with a payload of 22 bytes. The TOA of the devices was 0.6s. The hidden sector amounts to roughly $\frac{4}{5}$. It is calculated by every device based on the experiments from Section 4.3.3. The environment provides for setting the position, initial energy and persistence values. The position setting for every device requires an input of x,y,z-coordinates. The data rate of the devices is set automatically depending on the distance of the device from the gateway. The initial energy per device was set to the value of 1 Joule. The devices had a transmission rate varying from 66ms to 132ms.

### 5.3.1. Centralized Method

The centralized p-CSMA network was modelled in NS3. Figure 5.10 details the throughput, probability of success and energy consumption of the network under varying persistence values. As the TOA is less than the MATLAB simulation the number of packets being transmitted per device increases. When using p-CSMA the optimum throughput is observed at 0.3. This difference between the MATLAB and NS3 values can be attributed to the functioning of LoRaWAN. If the gateway PLL is locked onto a specific packet, two packets with the same data rate may not collide. Rather, the packet that arrived first will be accepted by the gateway and the second packet dropped. Figure 5.10 depicts the throughput when the devices are all tuned to the same transmission configuration and have a constant transmission period. It is observed that an initial persistence of 0.5 gives maximum throughput when the number of devices being serviced are also large.




(a) Throughput

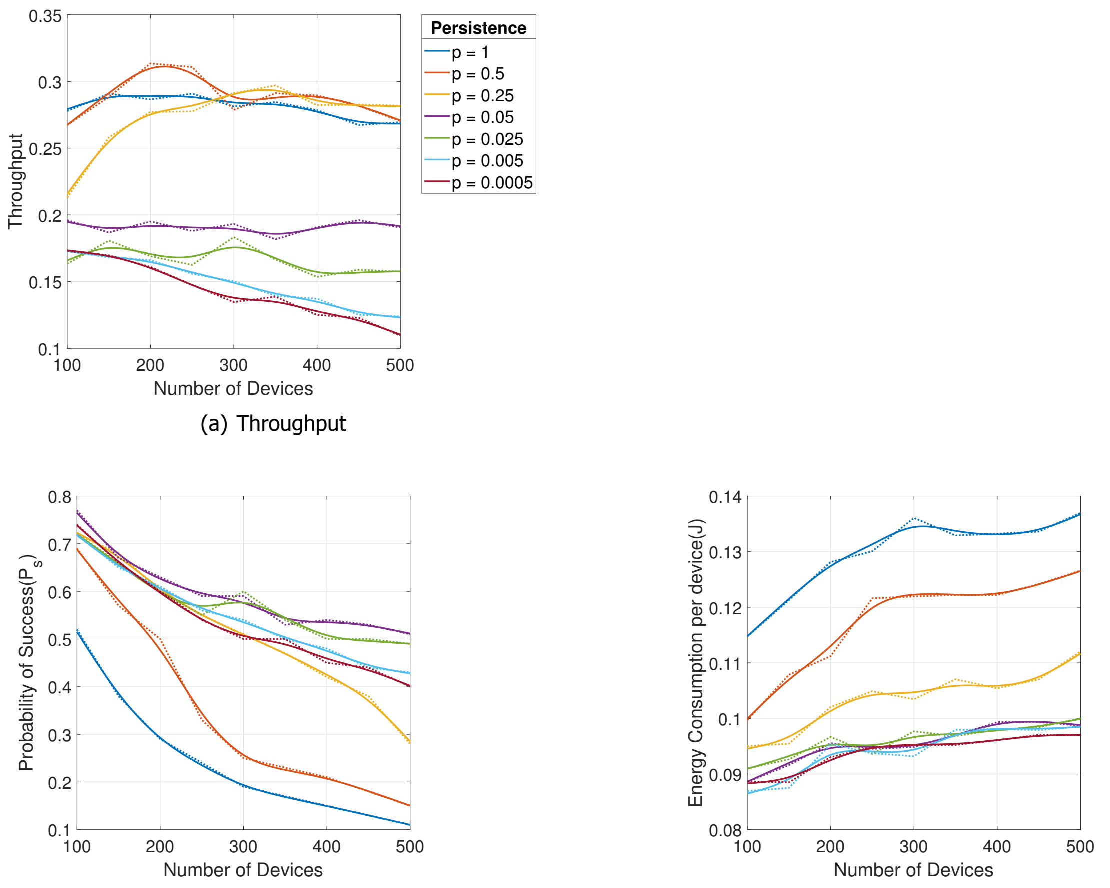
(b) Probability of Success

(c) Energy Consumption

Figure 5.10: NS3 results for Centralized Method

### 5.3.2. Distributed Method

The distributed p-CSMA network was tested with different persistence values. The configuration was the same as the centralized network. Unlike the centralized method the devices however, were able to decrease their own persistence. Figure 5.11 compares the throughput, probability of success and energy consumption of a distributed p-CSMA network. At the 150 devices mark, the persistence was observed to have lowered and final persistence values were in the range of 0.25 to 0.35. The outcomes of the NS3 simulation are a close estimation of network behavior in a real-world deployment.




(a) Throughput

(b) Probability of Success

(c) Energy Consumption

Figure 5.11: NS3 results for Distributed Method

Energy consumption of the devices was also studied in the experiments performed in NS3. The work of Kouvelas et al. [27] has been further developed to include an energy module. It was observed that as the number of devices increased the time spent by each device for sensing was larger, resulting in an increase in the average energy consumed per device. For higher persistence and larger numbers of devices the energy consumption is higher. If either the persistence or number of devices decrease, the energy consumed per device decreases linearly.

### 5.3.3. Hybrid Method

Figure 5.12 compares the hybrid p-CSMA vs ALOHA with respect to throughput, energy and probability of success. As observed in Figure 5.12(a) the throughput of hybrid p-CSMA is substantially higher than that of ALOHA devices. This is especially true as the number of devices being serviced by the gateway increases. The throughput in ALOHA drops exponentially as the number of devices increases. However, the throughput of the hybrid p-CSMA appears to drop gradually. The probability of successful transmission is also higher in the hybrid method due to lower probability of collision in CSMA. This is observed in Figure 5.12(b). When 100 devices are being serviced by the gateway the $P_s$ in ALOHA is

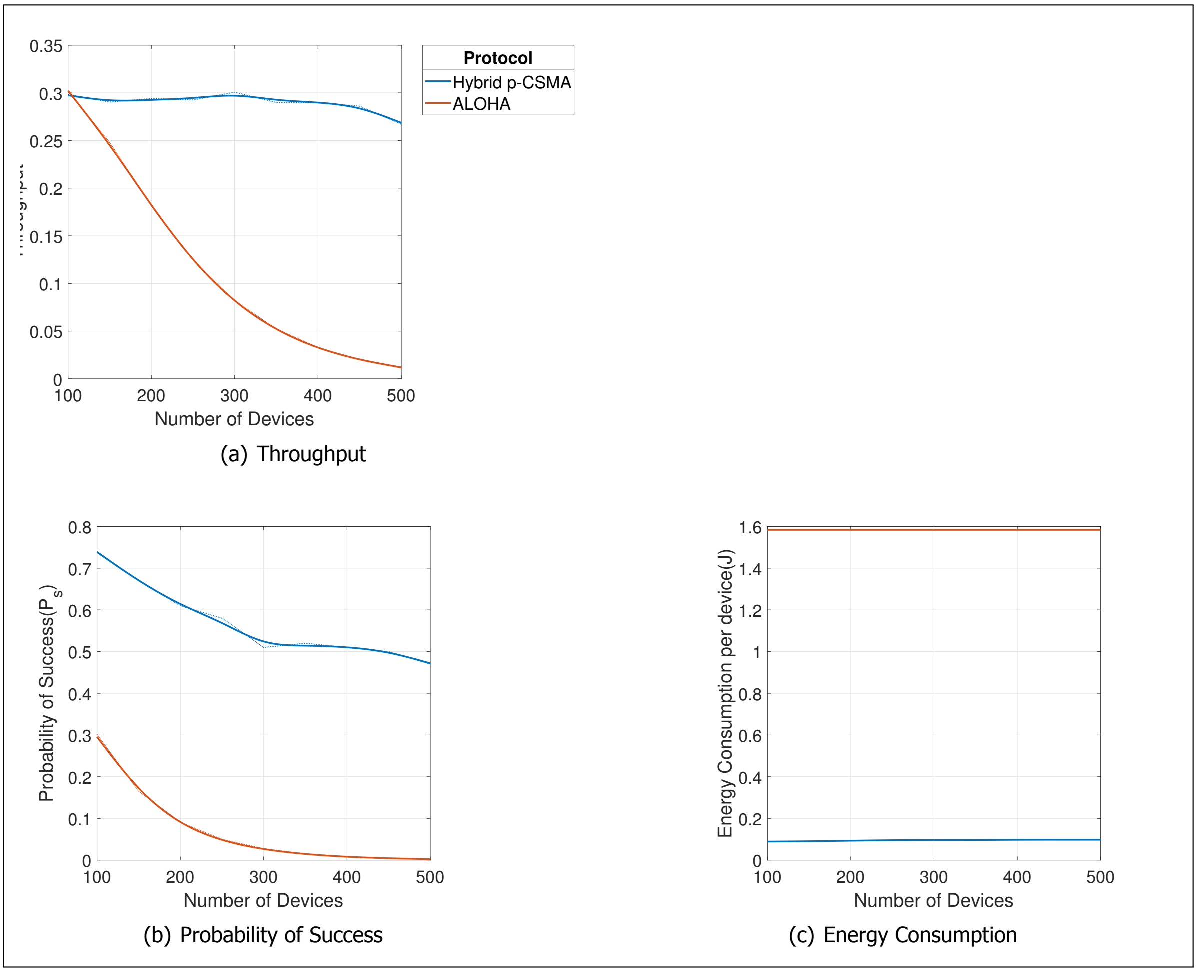



Figure 5.12: NS3 results for Hybrid Method

0.3. In comparison, the hybrid p-CSMA has $P_s$ equal to 0.74. Figure 5.12(c) is a comparison of the total energy spent by a device per hour. A p-CSMA device spends more energy sensing and less energy transmitting as compared to ALOHA, resulting in lower average energy consumption.

## 5.4. Summary

Attributes of Centralized Method:

- Gateway functioning must be updated.
- Effective for uniform distribution.
- Not ideal for random distribution as devices do not adapt to changes in their sensing range.
- Energy consumed per device is highest for this configuration.
- Persistent techniques yield a maximum throughput of 0.31 as observed in the NS3 simulations.
- The probability of success drops gradually as compared to distributed methods.

Attributes of Distributed Method:

- Gateway functioning remains unchanged.
- Devices lower persistence or backoff values when channel is busy, requiring adequate computational power.

- As densely populated device areas to have much lower persistence or backoff values if distribution is non-uniform, thereby limiting the number of devices that will successfully transmit.
- Higher persistence leads to higher energy consumption.
- Lowest energy consumed in np-CSMA.
- Probability of success decreases with higher persistence, but throughput is observed to be maximum as the highest number of packets are transmitted.
- Persistent techniques yield a maximum throughput of 0.31 as observed in the NS3 simulations.
- The maximum probability of success is observed to be 0.75 for p equals 0.05.

Attributes of Hybrid Method:

- End-devices and gateway firmware require updating.
- For larger number of packets lower persistence values allows for higher probability of success.
- It is a dynamic network and does not require a uniform distribution to reach optimal throughput.
- Energy efficiency vs throughput is optimal.
- Persistent techniques yield a maximum throughput of 0.31 as observed in the NS3 simulations.
- The probability of success drops gradually as compared to distributed methods.

CHAPTER 6

# Conclusion and Future Work

The Internet of Things continues to expand rapidly across many industries and applications. This growth in data, networks and wireless communication however, comes with high amounts of power consumption. Due to this factor IoT applications are likely to be costlier, inefficient and more time-consuming in the long run. This is where developments in the LoRa technology can revolutionize IoT.

With a forecast to reach 28 billion units of connected devices in 2020, the need for technologies like LoRa and NB-IoT has soared. LoRa allows thousands of IoT and M2M devices to be connected together over long ranges by a single gateway. As the number of connected devices starts to increase, the traffic handling capacity of a LoRa gateway can deteriorate. This research has been carried out within the EU region and is therefore subject to its regulatory constraints. These constraints when coupled with long TOA due to CSS in LoRaPHY, and ALOHA like behavior of LoRaWAN lead to scalability limitations. The aim of this thesis is thus:

'To study the possible MAC layer implementation that results in higher throughput for LoRaWAN'

One of the best known methods to improve channel throughput in ALOHA is to implement carrier sensing mechanisms. The paper by Tobagi and Kleinrock [15] proved how throughput increased when carrier sensing mechanisms were applied in multiple access networks. In order to optimize LoRaWAN, carrier sensing mechanisms has been adopted across three identified network scenarios - centralized, distributed and hybrid. p-CSMA and np-CSMA protocols were adapted to fit the behavior of each of these scenarios. Their algorithms were simulated and analyzed for throughput and energy efficiency.

Traditionally, LoRa devices are not designed to provide for the implementation of carrier sensing protocols. However, they are able to sense the presence of a LoRa preamble by means of an inbuilt feature called CAD. During CAD mode, devices capture the waveform on the channel and compare it with their own preamble structure. Based on the result they attempt to predict the data rate of the packet on the channel and set a CADDetect flag. RSSI values are also measured. It was found that beyond LoS, RSSI was not a good indicator of channel activity. However based on the CADDetect value it was possible to predict the presence of a packet with sufficient accuracy. The accuracy of prediction diminished as the distance between devices increased. Lower data rates exhibited higher sensing ranges.

## Future Work

This work is a first step into implementing unslotted carrier sensing MAC protocols in LoRaWAN. It provides a foundation for improving throughput under high traffic load. It uses current JA and ADR cycles to relay limited information between the gateway and end-devices. It shows the effect of the hidden terminal problem on the throughput, but does not attempt to employ any techniques to solve it. The issue of collisions due to hidden nodes is another area that could lend itself for further experimentation and analysis towards improvements in LoRaWAN.

Class A LoRa devices are widely used for deployment in most LoRaWAN networks. As their transmission protocol is unslotted in nature, this thesis focused on unslotted CSMA. The presence of extra scheduled receive windows in Class B devices can make them suitable for slotted CSMA techniques. The latest LoRaWAN specification 1.0.3 [30] allows the devices to obtain the epoch time of the network server, thereby allowing for synchronization between devices. As inferred from the paper by Kleinrock et. al [15], slotted CSMA could potentially double the throughput and increase efficiency.

The experiments for carrier sensing range were conducted with SX1276 chipset and standard LoRa antennas. Testing with alternate antennas having varying gains could potentially affect the sensing range and consequently the hidden terminal problem in the network. This could eventually improve channel efficiency.

In conclusion, implementing carrier sensing in LoRaWAN has the potential to improve scalability and performance of LoRaWAN applications and lead to a more robust communication network. However, there is still much to be studied.

# Acronyms

**ABP** Activation by Personalization. 13
**ADR** Adaptive Data Rate. 13, 14, 25, 27, 51
**AES** Advanced Encryption Standard. 9
**AppEUI** Application Extended Unique Identifier. 13
**AppKey** Application Key. 13
**AppSKey** Application Session Key. 13

**BW** Bandwidth. 6, 8, 12, 20, 30, 46

**CAD** Carrier Activity Detection. v, 3, 4, 7, 15, 23, 29–32, 34–36, 38, 39, 46, 51
**CHIRP** Compressed High Intensity Radar Pulse. 5, 6, 32, 36
**CR** Coding Rate. 6, 8, 12, 20, 46
**CSMA** Carrier Sense Multiple Access. v, 3, 15–17, 21, 22, 27, 39, 40, 44, 48, 51
**CSS** Chirp Spread Spectrum. 2, 5–7, 51

**DevAddr** Device Address. 13
**DevEUI** Device Extended Unique Identifier. 13
**DR** Datarate. 6, 8, 14, 20, 21, 23, 28, 31, 32, 34–42, 44, 47

**FSK** Frequency Shift Keying. 7, 8

**ISM** Industrial, Scientific, Medical. v, 2, 9, 19, 28

**JA** Join Accept. 11–13, 25, 27, 28, 51
**JR** Join Request. 11, 13

**LBT** Listen Before Talk. 20, 21
**LoRa** Long Range. v, 1–9, 12, 13, 15, 17, 19–21, 23, 25, 27, 29–31, 35, 36, 39, 51, 52
**LoRaWAN** LoRa Wide Area Network. i, v, 1–5, 9, 11, 13–16, 19–25, 30, 31, 36, 38, 39, 41, 46, 47, 51, 52
**LoS** Line of Sight. 15, 34, 35, 37, 38, 51
**LPWAN** Low-Power Wide-Area Network. v, 1, 7, 15, 23

**MAC** Media Access Control. 2, 3, 9, 11, 19, 21, 46, 51

**np-CSMA** non-persistent Carrier Sense Multiple Access. v, 3, 22, 24–27, 39, 41–45, 50, 51
**NwkSKey** Network Session Key. 13

**OTAA** Over-the-Air-Activation. 13

**p-CSMA** persistent Carrier Sense Multiple Access. v, 3, 22, 24, 25, 27, 39, 41, 42, 44–49, 51
**PLL** Phase Locked Loop. 6, 7, 29, 30, 47
**PSA** Polite Spectrum Access. 20

**RSSI** Received Signal Strength Indicator. 20, 29, 30, 34–39, 46, 51

**SF** Spreading Factor. 6, 8, 12, 15, 30, 32, 36, 38, 46
**SRD** Short Range Devices. 2, 19, 20

**TOA** Time on Air. 2, 8, 14, 20, 21, 23–25, 27, 28, 41, 47, 51

# Bibliography


[1] K. Ashton, *That 'internet of things' thing,* RFID Journal (2009), Jun 22, 2009, [Online; accessed 18-February-2018].

[2] Ericsson, *Ericsson mobility report,* https://www.ericsson.com/assets/local/news/2016/03/ericsson-mobility-report-nov-2015.pdfl, [Online; accessed 18-February-2018].

[3] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, *Understanding the limits of lorawan,* IEEE Communications Magazine **55**, 34 (2017).

[4] J. P. Bardyn, T. Melly, O. Seller, and N. Sornin, *Iot: The era of lpwan is starting now,* in *ESSCIRC Conference 2016: 42nd European Solid-State Circuits Conference* (2016) pp. 25–30.

[5] C. E. C. Committee, *Erc recommendation 70-03,* .

[6] S. Corporation, *Sx1272/3/6/8: Lora modem-designer's guide,* http://www.semtech.com/images/datasheet/LoraDesignerGuide.pdf (2013), [Online; accessed 23-November-2016].

[7] *What is lora®?* "https://www.semtech.com/lora/what-is-lora", "[Online; accessed 18-February-2018]".

[8] N. Sornin, M. Luis, T. Eirich, T. Kramp, and O. Hersent, *Lorawan™ specification 1.0.1,* (2015).

[9] S. Corporation, *Sx1272/3: Datasheet,* https://www.semtech.com/uploads/documents/sx1272.pdf (2013), [Online; accessed 23-November-2016].

[10] K. Mikhaylov, J. Petaejaejaervi, and T. Haenninen, *Analysis of capacity and scalability of the lora low power wide area network technology,* in *European Wireless 2016; 22th European Wireless Conference; Proceedings of* (VDE, 2016) pp. 1–6.

[11] O. Georgiou and U. Raza, *Low power wide area network analysis: Can lora scale?* IEEE Wireless Communications Letters **6**, 162 (2017).

[12] M. C. Bor, U. Roedig, T. Voigt, and J. M. Alonso, *Do lora low-power wide-area networks scale?* in *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems* (ACM, 2016) pp. 59–67.

[13] N. Varsier and J. Schwoerer, *Capacity limits of lorawan technology for smart metering applications,* in *Communications (ICC), 2017 IEEE International Conference on* (IEEE, 2017) pp. 1–6.

[14] S. Corporation, *An1200.22 lora™ modulation basics,* https://www.semtech.com/uploads/documents/an1200.22.pdf (2015), [Online; accessed 23-November-2016].

[15] F. Tobagi and L. Kleinrock, *Packet switching in radio channels: Part ii–the hidden terminal problem in carrier sense multiple-access and the busy-tone solution,* IEEE Transactions on Communications **23**, 1417–1433 (1975).

[16] F. Tobagi and L. Kleinrock, *Packet switching in radio channels: part ii–the hidden terminal problem in carrier sense multiple-access and the busy-tone solution,* IEEE Transactions on communications **23**, 1417 (1975).

[17] J.-H. Huang and L. Kleinrock, *Throughput analysis and protocol design for csma and btma protocols under noisy environments,* IEE Proceedings I Communications, Speech and Vision **139**, 289 (1992).

[18] I. Ramachandran and S. Roy, *Analysis of throughput and energy efficiency of p-persistent csma with imperfect carrier sensing,* GLOBECOM 05. IEEE Global Telecommunications Conference, 2005. (2005), 10.1109/glocom.2005.1578410.

[19] R. Mackenzie and T. Ofarrell, *Throughput and delay analysis for p-persistent csma with heterogeneous traffic,* IEEE Transactions on Communications **58**, 2881–2891 (2010).

[20] T. H. Kim, J. Ni, R. Srikant, and N. H. Vaidya, *On the achievable throughput of csma under imperfect carrier sensing,* 2011 Proceedings IEEE INFOCOM (2011), 10.1109/infcom.2011.5934962.

[21] A. Duda and T.-H. To, *Simulation of LoRa in NS-3: Improving LoRa Performance with CSMA,* in *IEEE ICC* (Kansas City, United States, 2018).

[22] L. Kleinrock and F. Tobagi, *Packet switching in radio channels: Part i–carrier sense multiple-access modes and their throughput-delay characteristics,* IEEE Transactions on Communications **23**, 1400–1416 (1975).

[23] E. T. S. I. 2012, *Final draft etsi en 300 220-1 v2.4.1 (2012-01),* .

[24] *Ieee standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements - part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications,* IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012) , 1 (2016).

[25] P. Karn *et al.*, *Maca-a new channel access method for packet radio,* in *ARRL/CRRL Amateur radio 9th computer networking conference*, Vol. 140 (1990) pp. 134–140.

[26] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, and M. Pettissalo, *On the coverage of lpwans: range evaluation and channel attenuation model for lora technology,* in *ITS Telecommunications (ITST), 2015 14th International Conference on* (IEEE, 2015) pp. 55–59.

[27] N. Kouvelas, V. Rao, and R. R. V. Prasad, *Employing p-csma on a lora network simulator,* CoRR **abs/1805.12263** (2018), arXiv:1805.12263 .

[28] D. Magrin, M. Centenaro, and L. Vangelista, *Performance evaluation of lora networks in a smart city scenario,* in *2017 IEEE International Conference on Communications (ICC)* (2017) pp. 1–7.

[29] D. Magrin, L. Vangelista, and M. Centenaro, *Network level performances of a LoRa system*, Ph.D. thesis (2016).

[30] L. A. T. Committee, *Lorawan™ specification 1.0.3,* (2018).