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Performance Evaluation of a LoRaWAN Towards Development of an Optimised ADR (Adaptive Data Rate) Model

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Abstract

The accelerating growth of the Internet of Things (IoT) has led to the development of many different communication protocols to enable the most optimal environment for the nature of IoT. Requiring long range and low power communication abilities, has resulted in LPWANs (low-power WANs); one such LPWAN is LoRaWAN (Long Range WAN) which is studied in depth in this thesis.

The thesis is done in collaboration with The Things Network (TTN), a crowd-sourced LoRaWAN expansing over 6 continents. The data retrieved from the TTN NOC (Network Operations Centre) has played a crucial role in this thesis, as it provides the basis for studying the working and performance of a LoRaWAN.

The aim of this study is to use performance evaluation of the network to develop an Adaptive Data Rate (ADR) model which will modify the transmission parameters to improve the performance of the network, in terms of the ratio of received and sent packets (called Data Extraction Rate - DER), while attempting to maintain minimal cost of transmission, in terms of transmission power and usage of bandwidth by measuring the airtime used in transmission.

Extensive evaluation and analysis of the NOC data is performed and detailed in this report, followed by a modified ADR model which theoretically will improve the DER of the network. This ADR model is verified by modelling the performance of devices on the network with the usage of the proposed ADR model and without. This theoretical verification proves that the DER of the network improves when the transmission parameters are varied in accordance with the proposed ADR model.

Acknowledgements

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Chapter 1

Introduction

1.1 Technology Background

The term 'Internet of Things (IoT)' was coined in 1999 by Kevin Ashton to describe his usage of RFID in Procter and Gamble's supply chain. However it was not until the late 2000's when this concept erupted when there were more devices connected to the Internet than people in the world [1]. This count is only increasing with time, and the most important enabler is the availability of a suitable network. For many applications, a long-range network is desired; and due to the large number of devices, a low-cost and low-power solution is required.
One such technology is called LoRaWAN, a MAC layer protocol developed on LoRa modulation technology. LoRa stands for LOng RAnge and was developed by a French company, Cycleo and the technology was later acquired by Semtech. LoRa is based on Chirp Spread Spectrum modulation that allows long ranges of transmission (up to 10km in rural areas) and is robust against multipath and fading effects.
The Things Network (TTN) [2] has initiated a worldwide community to build an open, crowd-sourced LoRaWAN, allowing the users to have complete control over their devices on the network.

1.2 Research Problem

The Things Network was founded in 2015, and has grown to consist of over 3000 gateways all over the world owned and used by almost 40,000 users and over 20,000 different applications. Previously, this network has been analysed by Blenn and Kuipers in 2016 [36], when the network was in an early stage of development consisting of only around 700 gateways. As the network has increased multi-fold, this is a unique opportunity to analyse the scaling and properties of the changing network. To evaluate the growth of a LoRaWAN, the same analysis is repeated and the results are compared

to draw insights which can further help in improving the performance of the network. Further, the impact of environment is studied, as well as the geographical spread of the network in the Netherlands.
The traffic analysis performed, can help gauge the reasons for negative impact on the performance of the network. The transmission parameters are one such factor that can improve the performance and are also in the hands of the user. The Adaptive Data Rate (ADR) algorithm implemented in the network varies these transmission parameters to achieve the required performance. This algorithm is responsible for varying the data rate and the transmission power to ensure the lowest cost of transmission and a high success rate. In the current implementation, the low cost of transmission is given higher priority, and this leads to more frames being missed and requiring retransmission. This thesis focuses on providing the required minimum performance, while maintaining as low cost of transmission as possible.

1.3 Organization

This thesis starts with a brief overview of the technology in question - LoRaWAN - in chapter 2. This chapter also covers the The Things Network (TTN) implementation of LoRaWAN, describing in detail the ADR implementation in TTN. The next chapter, chapter 3, describes the data retrieved from the Network Operations Centre (NOC) of TTN, and also provides sources and explanation of all the external (non-TTN) data used during this thesis. The initial data analysis and insights are covered in chapter 4, including the comparative analysis describing the changes observed in the data, the impact of external influences on the network, and the geographical analysis of the network. The next 2 chapters dive into the development of a modified ADR model; the first of these, chapter 5, provides in-depth analysis of the performance of the network with the current implementation of ADR and the transmission parameters when the desired performance is observed. Chapter 6 describes the model development along with verification of the working of the modified ADR, wherever relevant data can be modelled. The thesis is concluded in chapter 7.

Chapter 2

LoRa(WAN) Description

This chapter describes the technology which is analysed in the following chapters. LoRa is the underlying PHY layer of LoRaWAN and descriptions of both LoRa and LoRaWAN are presented below. The last section in this chapter describes The Things Network (TTN) as this thesis is in collaboration with TTN and the data used in this thesis is retrieved from the TTN Network Operations Centre (NOC).

2.1 LoRa

LoRa is a proprietary wireless communication technology owned by the French company, Semtech. It is a type of spread spectrum modulation and works on license-free radio frequency bands. Official LoRa documentation is very limited due to its proprietary nature, however some people have analysed it, for example Matt Knight reverse engineered LoRa and described what he learnt in his research available on his GitHub account [3]. This section describes the LoRa modulation scheme referenced from this paper and some others.

2.1.1 LoRa modulation

The Chirp Spread Spectrum (CSS) modulation scheme is used in LoRa. A spread spectrum modulation makes use of the entire frequency spectrum available for transmitting the signal. The frequency of transmission is varied using a technique called frequency hopping, and follows a pre-decided sequence so that the signal can be decoded at the receiver.
CSS is a type of spread spectrum modulation where the '1' and the '0' bits are modulated using an up-chirp or a down-chirp. A chirp is a signal with linear increase or decrease in frequency. In figure 2.1, a LoRa encoding of a frame is displayed, showing the 8 up-chirps representing the preamble, 2 down-chirps representing the synchronisation bits, followed by payload

encoding. This figure is referenced from Saksham Ghosalya's website [4].

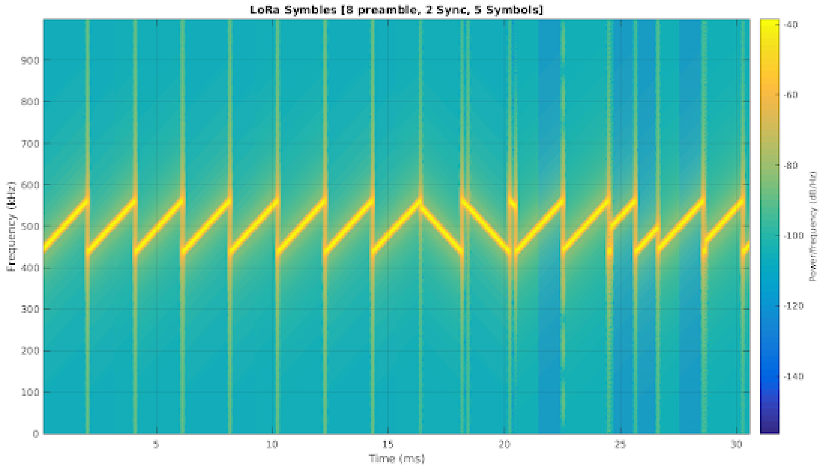

Figure 2.1: LoRa encoding of a frame [4]

There are 2 main parameters in the CSS type of modulation. One is the spreading factor which describes the rate at which the frequency changes. The lower the rate of change, the clearer the signal is to detect. However, with a higher rate, more data can be transmitted. The second parameter is the bandwidth, or the range over which the chirp is spread. The chirp uses up the entire bandwidth provided and is hence resilient to multi-path fading. The larger the bandwidth, the better the quality of the received signal. However, this uses up scarce resources. Detailed description of these parameters will be provided in the section 2.1.2. LoRa is not affected by the Doppler effect seen in mobile applications, because the chirps are linear causing the frequency offset to be equal to timing offset. With the CSS, it also employs FEC (forward-error correction), which uses redundant information to reduce and control the amount of error in the received signal.

2.1.2 Transmission Parameters

As seen from section 2.1.1, LoRa uses different transmission parameters to describe the properties of the message sent. Controlling these parameters can help us improve the performance of the network by enabling the most efficient combination. There are 3 main factors which describe the performance of LoRaWAN - a high transmission range, low transmission power and high resilience to interference and noise. Depending on the requirements of the application, a trade-off has to be made between the 3 factors. This is explained in detail below.

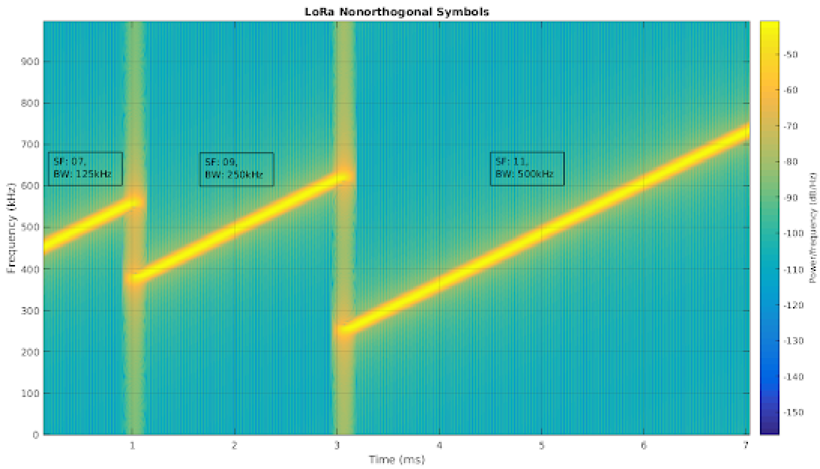

Figure 2.2: Parameters defining CSS modulation features [4]

Transmission Power

The power with which the transmitter sends the signal in dBm. It ranges from -4dBm to 20dBm on a LoRa transceiver. The lower this value, the longer the battery of the device lasts. However, a lower transmission power can decrease the range of transmission.

Carrier Frequency

The centre frequency of the carrier signal depending on the frequency band used by the application and the geographical location. LoRa uses licence free channels, for example in Europe, the EU868 frequency band is used which range from 863 to 870 MHz. This band consists of 9 uplink channels, and for downlink all 9 of these channels can be used with an additional channel. More information about uplink and downlink messages will be provided in section 2.2.3 of this chapter. These channels can be used simultaneously for different transmissions. Similarly, different geographical regions have different frequency bands available for use by LoRa.

Spreading Factor

As described above, the Spreading Factor (SF) describes the rate of frequency variation in chirps. SF values range between 7 and 12 and enable orthogonality, which allow multiple transmissions on the same channel. By increasing the SF, the range increases and the data rate decreases. However, lesser information is sent using the higher SF as the value of airtime (as explained in section 2.2.8) is higher, and each device has a restriction on how much it can use transmit per day as explained in section 2.2.4. The SF describes the length of a chip which is 2^{SF} and divided by SF to give the length of a code. A chip is a single pulse in communication, representing the 0 or 1 bit.

Bandwidth

Bandwidth describes the range provided to the chirp and 3 different settings are available, 125 kHz, 250 kHz, and 500 kHz. The chip rate of transmission is decided based on the bandwidth. A bandwidth of 125 kHz denotes a chip rate of 125 *kcps*. A larger bandwidth enables a better quality signal as it is more resilient to multi path fading.
LoRaWAN abstracts over the SF and bandwidth to provide a parameter called Datarate. This will be described in section 2.2.8.

Coding Rate

The value of Coding Rate (CR) denotes the amount of FEC (Forward Error Correction), which in turn describes the receiver sensitivity. When the CR = 0, there is no FEC. The values of CR range from 0 to 4 where the code rates are 0, 4/5, 2/3, 4/7 and 1/2. In these values, the numerator represents the number of useful bits, the denominator represents the number of output bits, and the difference is the number of redundant bits which enables correction abilities in the receiver. With an increase in CR, there is a decrease in data rate.

2.2 LoRaWAN

LoRaWAN describes a LPWA (Low Power Wide Area) networking protocol designed on the LoRa PHY. LoRaWAN, an open source global MAC protocol, was introduced by the LoRa Alliance [5], a non-profit association of over 500 organizations which maintain the LoRaWAN.

2.2.1 LoRaWAN protocol

The LoRaWAN protocol has 3 modes of communication and the class A mode is the same as the ALOHA protocol and is asynchronous. The other classes (B and C) are modified versions of the ALOHA protocol. This enables communication at programmed intervals and reduces battery consumption. The communication intervals are further described in section 2.2.5, where different communication classes in LoRaWAN are explained.

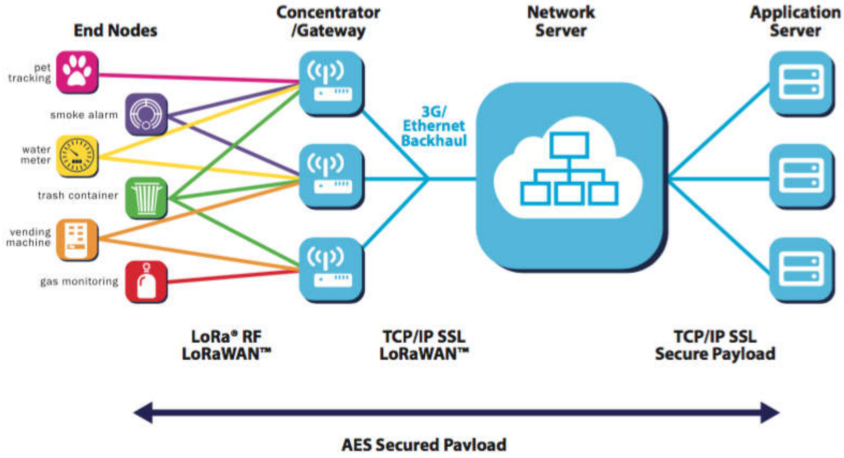

Figure 2.3: The Network Architecture of a LoRaWAN [6]

2.2.2 Network Architecture

The LoRaWAN network architecture is a star-of-stars topology. There are 4 main components of a LoRaWAN network - end devices (also known as nodes), gateways, network server and the application displayed in figure 2.3, referenced from [6].

End Devices

The end devices interact with the environment and form the most voluminous part of a LoRaWAN. There are 3 classes of end devices which are described in section 2.2.5. The devices have unique identifiers of 64 bit length called DevEUI. The devices are given a non-unique 32 bit device address, DevAddr, every time the device joins the network. More details about the joining procedures are provided in section 2.2.7.

Gateways

The gateways form the bridge between the end device and the network. The gateways and end device use the LoRaWAN protocol for communication, however the back-haul network from the gateway to the network server may be cellular, WiFi or anything else. The gateways blindly transmit all LoRaWAN packets received correctly from the devices to the network, and do not perform any kind of filtering. The gateways are given a unique 64 bit identifier called the GatewayEUI.

Network Server

The network server handles the packets and re-directs them to the right application, it handles any parameter selection, sends acknowledgements when required, and is mainly responsible for the performance of the network. It filters out packets from devices which are not on the same network and duplicate packets as well. More about the back-end of the network is described in section 2.3.1. The Adaptive Data Rate (ADR) algorithm is also implemented in the network server. This algorithm adapts the transmission parameters to optimize the network use and improve performance. The ADR is described in section 2.2.9.

Applications

The devices are programmed to perform an operation that is a part of an application. The network server sends the packets to the application for processing and the application sends any instructions to be sent to the device to the network server which forwards it to the gateway and then gets sent to the end device. Applications have unique identifiers called the AppEui.

2.2.3 Types of packets

There are mainly 2 types of packets - uplinks and downlinks. Uplink frames are sent from end devices to the network and downlink frames are sent from the network to the end device. There are 3 types of uplink frames - confirmed, unconfirmed and join-requests. Join-requests are sent when the device wants to connect to the network using the OTAA (over the air activation) technique. If the device is accepted by the network, the network sends a join-accept in response using a downlink frame. Activation techniques are described in more detail in section 2.2.7. Confirmed messages require an acknowledgement from the network whereas unconfirmed do not. Acknowledgements are sent using downlink frames. Any instructions f.e. to activate ADR, are also sent on downlink frames (ADR activation is not limited to the gateway, the node can request ADR on the uplink direction).

2.2.4 Duty Cycle Restrictions

As LoRaWAN uses licence free frequency bands for transmission, the government imposes restrictions per device on usage of the network so that no device occupies the network for too long and causes starvation. The restriction is posed on the duty cycle, which defines the percentage of time a device uses the resource. Generally, a 1% duty cycle is imposed, however this depends on the location. For example, in Europe, the frequency band is split into 5 sub-bands and 3 of these have a 1% duty cycle limit, 1 has 10% and the last one has a 0.1% duty cycle limitation. Further, the duty cycle of join-requests are limited to 1% by LoRaWAN. The duty cycle limitations implemented in the European licence free spectrum, EU868, can be seen in table 2.1. If the maximum duty cycle is d, and the air time is T_a, then the off-period (where the device must be silent) is denoted by

$$T_s = T_a(\frac{1}{d} - 1) \tag{2.1}$$

Sub-Band	Frequency Range (MHz)	Duty Cycle Restriction (%)
g	863.0 – 868.0	1
g1	868.0 – 868.6	1
g2	868.7 – 869.2	0.1
g3	869.4 – 869.65	10
g4	869.7 – 870.0	1

Table 2.1: Duty Cycle restrictions per sub-band in EU868

Duty cycle restrictions can be overridden if Listen Before Talk - Adaptive Frequency Allocation (LBT-AFA) is adapted on the device externally. This feature is not available on LoRaWAN,
The Things Network has its own restriction on the usage of resources, which is described in section 2.3.3.

2.2.5 Device Classes

There are 3 main device classes in LoRaWAN - class A, class B and class C, all 3 classes enable bidirectional communication between the device and gateway. All LoRaWAN devices are required to implement class A by default. The description and images in the following sections are referenced from LoRaWAN 1.1 specifications [7].

Class A

Class A devices control transmission, and when the end device (ED) has a packet to send, it initiates communication by selecting an available sub-band. Every uplink transmission is followed by 2 reception windows, RX1 and RX2, which provide the only downlink communication links for a class A device. The RX1 uses the same channel as the uplink transmission, whereas the RX2 uses a predefined channel. This can be visualised in figure 2.4. The use of this device restricts the gateway to have to wait for a reception to transmit any data to the ED.

Class B

In class B, the ED communicates with the gateway during the N ping slots in between 2 beacons sent by the gateway (every 128 s). A bounded delay

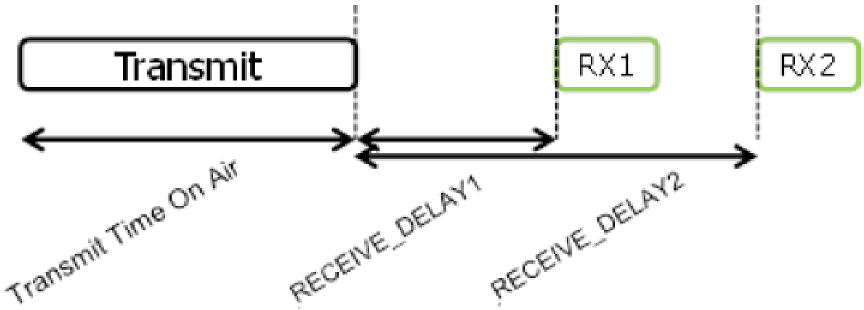

Figure 2.4: Class A Transmission

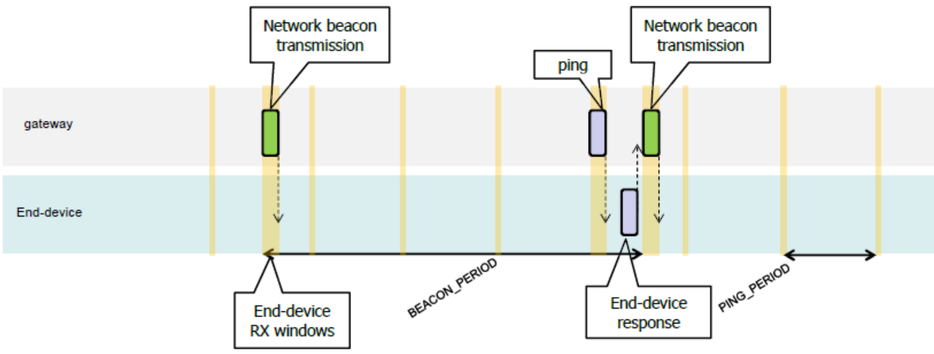

Figure 2.5: Class B Transmission

on the downlink communication is enabled by this. The time delay between 2 ping slots is called the ping delay. A 5.12 s long reserve period protects the beacon transmission. The beacon transmission can be visualised in figure 2.5.

Class C

EDs operating in class C are continuously listening for downlink communication from the gateway, hence providing the lowest latency at a high cost for downlink. This feature of class C devices can be visualised in figure 2.6.

2.2.6 Frame Format

The uplink and downlink frames have different frame formats. The frame format at the PHY is shown as well as the MAC layer format.

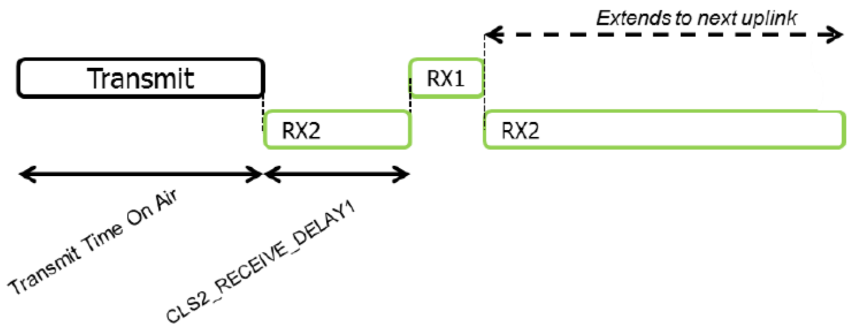

Figure 2.6: Class C Transmission

Preamble	PHDR	PHDR_CRC	PHYPayload	CRC

Figure 2.7: PHY frame format for uplink communication

Uplink Frame

The PHY frame format for uplink communication is shown in figure 2.7.
LoRa describes 2 types of packet formats - the explicit mode and the implicit mode. The explicit mode is the default setting, where a header is sent with the packet. This header contains information about the payload length, the code rate of FEC, and whether an optional 16 bit Cyclic Redundancy Check (CRC) is present in the frame. In implicit mode, the header is not included in the frame, as, the payload length, code rate and presence of CRC are known at both ends of the radio link. This reduces the airtime of the frame as the size of the packet is reduced. The CRC protects the payload integrity.
The contents of the PHYPayload is shown in figure 2.8. Depending on the type of message, the payload will vary.
The MHDR defines the type of message and the major encoding of the payload defining the format of the messages exchanged during the join procedure

MHDR	MACPayload	MIC

MHDR	Join-Request/ Rejoin-Request	MIC

MHDR	Join-Accept

Figure 2.8: PHYPayload frame format for different message types

Bit #	7..5	4..2	1..0
MHDR Bits	MType	RFU	Major

Figure 2.9: MHDR Format

Preamble	PHDR	PHDR_CRC	PHYPayload

Figure 2.10: PHY downlink frame format

2.9. There are 8 MAC message types defined in LoRaWAN - describing the direction of link, and whether it contains data.

Downlink Frame

The PHY frame format for downlink communication is shown in figure 2.10. Similarly, the downlink frame by default is sent in the explicit format. The only difference is that a CRC check is not performed at this stage to limit the duty cycle usage and comply with the ISM restrictions.
Figure 2.8 shows the PHYPayload for downlink frames as well. It is similar to the uplink frame format, except for in the case of a Join-accept where the MIC (Message Integrity Check) is encrypted in with the payload. The MIC is a digital key which ensures that the payload is secure during transmission.

As seen from figure 2.11, the MAC Payload consists of a frame header, an optional port field and optional frame payload. As seen in figure 2.12, the frame header (FHDR) consists of device address, frame control bits (eg. ADR and ADRACKReq), frame counter, and frame options. The ADR bits are available in frame control for being set/unset. The MAC commands with which the network server varies the DR and Tx power are sent in the frame options fields. Further details on the ADR process are available in section 2.2.9. The frame counter increments for every unique frame sent from the device, this helps with keeping track of how many packets have been dropped and how many are retransmitted.

2.2.7 Device Activation and Security

A LoRaWAN device has to be activated before it can participate in the network. There are 2 methods of activation - Over The Air Activation

FHDR	FPort	FRMPayload

Figure 2.11: MACPayload frame format

DevAddr	FCtrl	FCnt	FOpts

Figure 2.12: Frame Header frame format

(OTAA) and Activation by Personalization (ABP).

OTAA

Over the Air Activation provides a secure method of joining a LoRaWAN where a join procedure takes place. Once the activation is complete, the device is assigned a dynamic device address (DevAddr) to be used in the network. To start the join procedure, the end device sends a join-request to the network with which a DevEUI, a AppEUI (unique identifier of the Join Server that handles the application), a NwkKey (network key) and an AppKey (application key) are sent. The NwkKey and the AppKey are AES-128 root keys specific to the end device and are defined during manufacturing. The AppKey is used to derive the NwkSKey (network session key) and AppSKey (application session key) after the network responds with a join-accept message, consisting of a NetID (a 24 bit unique LoRa Alliance allocated identifier which identifies the network the device is on), DevAddr, DLSettings (consisting of downlink parameters), RxDelay (delay between transmission and reception), and CFList (an optional list of network parameters, which consists of the JoinNonce which helps in deriving the session keys). The 2 session keys are unique per device per session (after every OTAA); the NwkSKey is used to validate the communication between the end device and the network and performs the MIC check on the message; the AppSKey is used to encrypt and decrypt the payload.

ABP

In Activation by Personalization, the DevAddr and the security keys (AppSKey and NwkSKey) have to be hard-coded into the device. This procedure is less complicated than OTAA, however is less secure and is not the preferred method for joining the network. The AppEUI and the DevEUI are not required to be stored on the device for ABP type activation.

2.2.8 Data Rate Abstraction and Airtime

As explained in section 2.1.2, the spreading factor and the bandwidth are 2 parameters which control the range, speed and quality of communication. In Europe, 8 data rates are defined as seen in table 2.2.
The higher the data rate, the lower the communication range and the faster the messages are transmitted.
The amount of time taken by a message after it is transmitted and before it

DataRate	Modulation	Spreading Factor	Bandwidth	bits/s
0	LoRa	12	125	250
1	LoRa	11	125	440
2	LoRa	10	125	980
3	LoRa	9	125	1760
4	LoRa	8	125	3125
5	LoRa	7	125	5470
6	LoRa	7	250	11000
7	FSK			50000

Table 2.2: Data Rates defined in LoRaWAN for Europe

is received is called the airtime. The airtime is a function of the spreading factor, bandwidth, number of preamble symbols, payload length, and the coding rate. The airtime is higher for lower data rate values it decreases as the data rate increases.

$$T_{sym} = (\frac{2^{SF}}{BW}) \tag{2.2}$$

$$T_{preamble} = (n_{preamble} + 4.25)T_{sym} \tag{2.3}$$

$$\beta = \lceil (\frac{8PL - 4SF + 28 + 16 - 20H}{4(SF - 2DE)}) \rceil \tag{2.4}$$

$$PL_{sym} = max(\beta(CR + 4), 0) + 8 \tag{2.5}$$

$$T_{frame} = T_{preamble} + PL_{sym} \times T_{sym} \tag{2.6}$$

To compute airtime, the equations displayed in 2.2 to 2.6 are used [7]. In 2.2, first the time taken to transmit a symbol is computed based on the spreading factor and bandwidth of the transmission. In equation 2.3, the time taken to transmit the preamble is computed from the number of preamble symbols ($n_{preamble}$), and the T_{sym} computed from equation 2.2. Then equation 2.4 uses the payload length (PL), spreading factor, header enabling ($H = 0$, for enabled), and low data rate optimisation enabling ($DE = 1$, for enabled), to compute a variable (β), which is further used to compute the number of symbols in the payload (PL_{sym}) in equation 2.5. This equation also uses the coding rate (CR). Using the results from equations 2.2, 2.3 and 2.5, the airtime of a frame is calculated.

2.2.9 Adaptive Data Rate (ADR) Model

The Adaptive Data Rate (ADR) algorithm is a function implemented in the Network Server that enables the network to instruct the nodes to change transmission parameters such as transmission power, data rate, channel selection and retransmission limit to optimise transmission. The node indicates to the network that it requires a change in the transmission parameters via MAC commands on the uplink. On receiving this request, the network computes the suggested data rate based on link quality and sends MAC commands to the node with instructions for the data rate and transmission power variation.
ADR can only be implemented in a static node; if a node is constantly moving, the radio link metrics will vary causing oscillating values of data rate. The node is responsible for detecting whether it is in a state for ADR control. If it is, it sets the uplink ADR which sends indication to the network server to execute the ADR algorithm. If the network server is in a position to execute the ADR, the downlink ADR bit is set informing the end device of its availability. The LinkADRReq command sent by the network sends instructions to the device, and if implemented by the device, it acknowledges by sending the LinkADRAns command.
The end device needs to know if transmission is successful with the modified parameters. The ADRACKReq bit is used for this purpose. As the frame counter is incremented with each transmission, the ADR_ACK_CNT is also incremented. When this counter exceeds a limit (ADR_ACK_LIMIT) without receiving any downlinks, it sets the ADRACKReq bit, requiring an acknowledgement from the network server. If no acknowledgement is received within a delay period, it first increases transmission power to maximum, then step by step decreases the data rate. If there is still no acknowledgement, then it re-enables all channels. This is called data rate decay and it is a feature enabled in LoRaWAN. Hence, the implemented ADR model can only increase data rate and decrease transmission power to avoid oscillating values.
It is left to the network operator to implement an ADR model, however SemTech provides a recommended ADR model [8] using the SNR to modify data rates and power values. TTN implements the recommended SemTech model and it is explained in section 2.3.2.

2.2.10 Channel Mask

Channel mask (chMask) information is included as a part of the LinkADRReq command, which is used to encode the usable channels by the device for transmitting packets in the uplink direction.

As seen from figure 2.13, a value of 1 means that the corresponding channel is available for use.

Bit#	Usable channels
0	Channel 1
1	Channel 2
..	..
15	Channel 16

Figure 2.13: Channel State Table

2.3 The Things Network

The Things Network [27] is a community based initiative to create a world-wide LoRaWAN, maintained by and grown by community members and volunteers. As this thesis is in collaboration with TTN, the network data analysed is retrieved from the TTN Network Server and it is crucial to look at the specific features that TTN implements in LoRaWAN. These features will be described in this section.

2.3.1 Network Architecture

The Things Network is a Network server placed between the gateways and applications, providing a back end and handling routing and processing of messages as the devices may not support IP protocols (LoRaWAN). For the purpose of decentralization and enabling private network server set-ups, TTN has created a back-end architecture consisting of 5 main components - the Router, the Broker, the Handler, the Network Server and the Database. The network architecture can be seen in figure 2.14. In this thesis, the 3 components where data is processed and retrieved from are discussed in the following parts of the chapter - the Broker, the Router and the Handler.

Router

The Router receives all messages forwarded from gateways, manages gateway status and schedules downlinks. In class A communication, there are 2 receive windows. The router creates a score for each configuration using the signal strength, airtime, and transmissions that are already scheduled. The downlink is accordingly scheduled, on a less busy gateway (to not disrupt uplink messages). The traffic distribution is done based on the device addresses that are defined by the Broker.

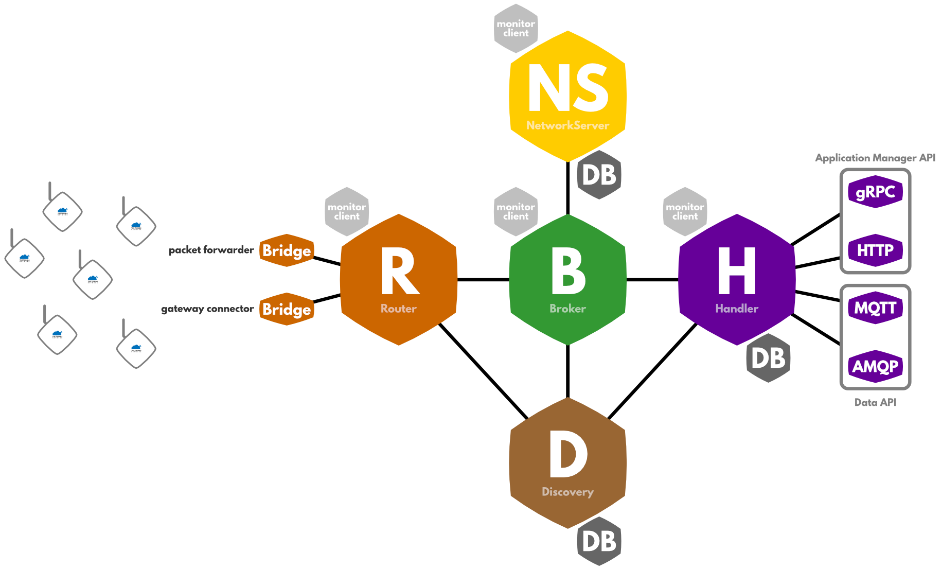

Figure 2.14: Back-end architecture of The Things Network

Broker

Mapping the packets to the right application is done by the Broker. It also forwards downlinks to the right Router for sending to the end device. The Broker is also responsible for removing duplicate messages as a frame can be received by multiple gateways. With the help of the Network Server, the Broker performs MIC checks to validate the messages. It validates the value of the frame counter and confirms that there is no replay attack or the gap between consecutive frames counters does not exceed the limit. The Broker uses the scores calculated by the Router to schedule the best downlink option for the frame.

Handler

The Handler manages data of the applications and receives the correct packets for the application from the Broker. It encrypts and decrypts the payload received from or sent to the application. The Handler decides whether a downlink response is required - either when the application has to send a payload to the device, when the uplink requires acknowledgement, or a MAC command is to be sent to the device from the Network Server. This message is forwarded to the Broker.

2.3.2 ADR

The currently implemented ADR model in The Things Network is the one recommended by SemTech in [8] and can be seen in figure 2.15. The algorithm works only on static devices operating on the EU868 ISM band. The 20 most recent uplink transmissions from the end device on which ADR is to be implemented are used to compute the suggested data rate. A message may be received at more than 1 gateway with varying SNR values. The inputs to the algorithm are:

- Frame counter values of the last 20 uplinks.
- The corresponding SNR value, the maximum SNR if the frame is received by multiple gateways.

Each new uplink for the corresponding link will eliminate the first entry from the 20 records, keeping the size of the records constantly 20.

$$SNR_{margin} = SNR_m - SNR(DR) - margin\_db \tag{2.7}$$

$$NStep = int(\frac{SNR_{margin}}{3}) \tag{2.8}$$

First, as seen in equation 2.7, the SNR margin (SNR_{margin}) is calculated by subtracting the sum of installation margin of a network (a device specific parameter - $margin\_db$) and the required SNR ($SNR(DR)$) 2.3 to demodulate a message received on the data rate the last frame from the maximum SNR (SNR_m) of all the SNR values of the 20 uplinks.

DataRate	**Required SNR**
DR0	-20
DR1	-17.5
DR2	-15
DR3	-12.5
DR4	-10
DR5	-7.5

Table 2.3: Required SNR to demodulate frames received on different Data Rates

As seen in equation 2.8, a variable called $NStep$ is computed from the SNR_{margin} by dividing it by 3 and only taking into account the rounded down integer part of the result. The $NStep$ represents the number of times the algorithm is executed. When $NStep$ is 0, it means that the device is already using the best possible transmission parameters. When $NStep$ is positive, it means that there is available margin to optimise the transmission parameters and shorten airtime and/or reduce the power. First the data rate is increased until maximum and then the transmission power is decreased until minimum. When $NStep$ is negative, it means that the link requires a boost in terms of airtime and/or power. In this case the transmission power is increased until maximum. The data rate is not modified as an automatic data rate decay has been implemented in LoRaWAN end devices.

Along with the data rate adaption, the ADR algorithm also enables the end device to repeat the transmissions by a number of times ($NbRep$) which is a function of the packet loss rate 2.9.

$$PktLossRate = \frac{Frame\_Counter(last) - Frame\_Counter(first) - 20}{Frame\_Counter(last) - Frame\_Counter(first)} \tag{2.9}$$

This is computed using the frame counter values of the extreme ends of the 20 records stored. The numerator indicates the number of frames that were missed in the course of the last 20 received uplinks. The denominator indicates the number of frames sent by the device in the same time-frame. Using thresholds for the packet loss ratio and the current NbRep (number of repetitions) value, the algorithm determines the new NbRep parameter. The maximum number of repetitions is limited to a maximum value of 3, as it is found to be a sufficient value for the current use cases as described in [8]. An approximate packet loss ratio of 10% is targeted.

2.3.3 Fair Access Policy

In addition to the duty cycle restrictions placed on the sub-bands in the licence free frequency bands, TTN also implements a fair access policy on users of TTN. This policy places upper limits on the uplink airtime to be 30s per day per end device and on the number of downlink messages to be 10 messages per day per end device.

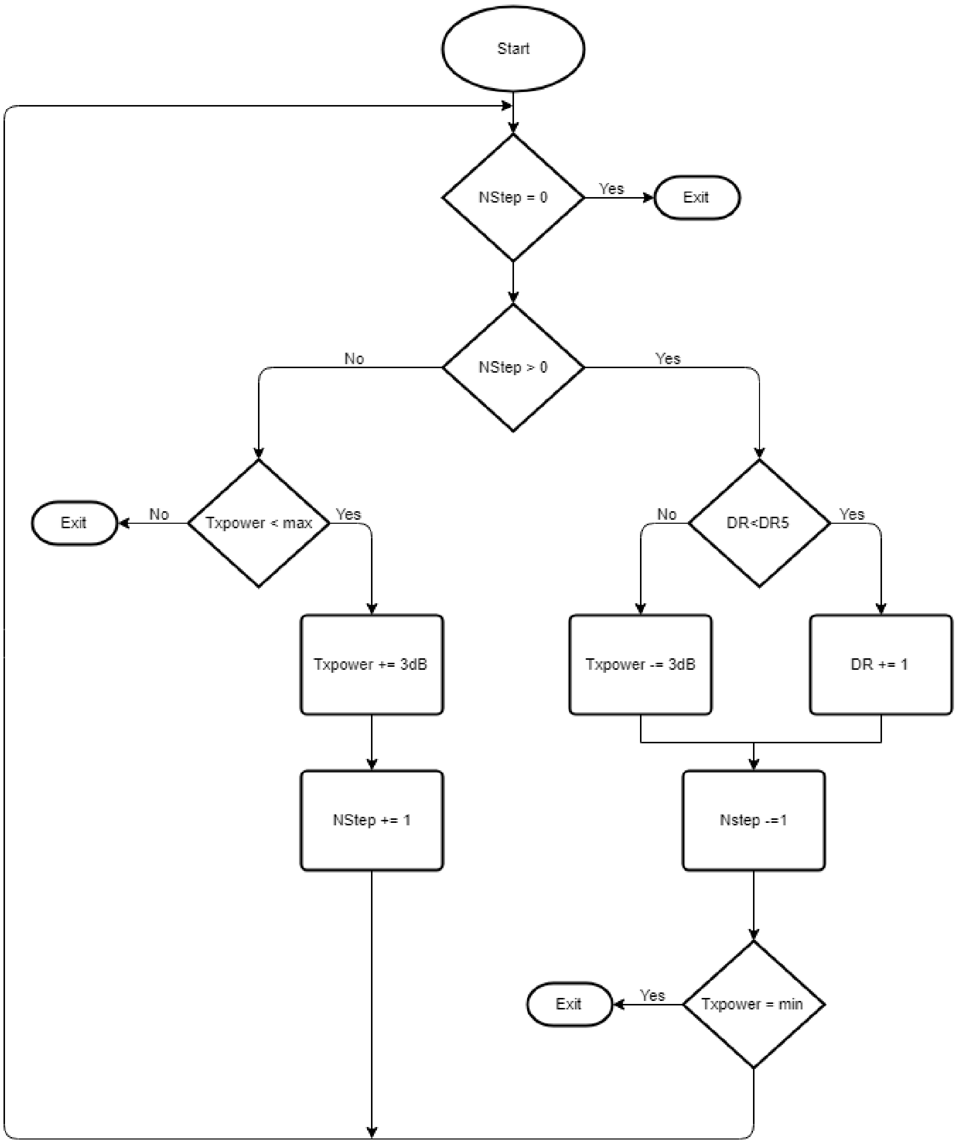

Figure 2.15: SemTech Recommended ADR model [8]

Chapter 3

Description of Data

This thesis makes extensive use of data retrieved from the NOC of The Things Network to analyse performance behaviour and characterise it to determine improvements using the Adaptive Data Rate model developed in chapters 5 and 6. This chapter describes the NOC data and any external datasets utilised.

3.1 TTN Data

The data retrieved from the NOC contains datasets corresponding to all 3 components in the back-end as described in section 2.3.1. The datasets are also categorised based on the direction of transmission, i.e., whether uplink or downlink. Apart from these, there is another dataset retrieved, which consists of periodic status updates sent from the gateway.

A description of the fields in the gateway_uplink dataset is presented in table 3.1. The dataset contains all uplink messages received at the gateways from devices. As a message from an end-device may be received by several gateways, the dataset consists of duplicate messages. The gateway and Router do not remove any messages - all messages are forwarded to the Broker. There are 3 categories of uplink messages which are described in the field *lorawan.message*. They are - *JOIN_REQUEST* (when the device wants to join the network using OTAA), *UNCONFIRMED_UP* (when the device does not require an acknowledgement from the network), and *CONFIRMED_UP* (when the device requires an acknowledgement from the network). The unique identifier of the device is registered at the gateway in the *lorawan.dev_eui* field when a 'JOIN_REQUEST' is sent. A device address is allotted by the Network Server to the device once it has joined the network. All further Uplink messages sent by the device use the device address stored in the *lorawan.dev_addr* field. The frame counter value is stored in the *lorawan.f_cnt* field. This value is set to 0 when the device joins the network and increments with every new message. It does not increment for retransmissions. The gateway uplink dataset also consists of the position of the gateway. The field *lorawan.coding_rate* contains the coding rate value which described the amount of Forward Error Correction (FEC) used for the transmission. The default value for LoRaWAN is 4/5.

Field	Description
name	component name and message type
time	timestamp at gateway when message was received
altitude	altitude of the position of the gateway
frequency	frequency of the channel used
id	unique identifier of the gateway
latitude	latitude of the position of the gateway
longitude	longitude of the position of the gateway
lorawan.airtime	time taken to transmit one frame
lorawan.app_eui	the unique identifier of the application for which the message is intended
lorawan.bandwidth	bandwidth used during the transmission
lorawan.coding_rate	coding rate used for that transmission
lorawan.dev_addr	the device address allotted to the end device
lorawan.dev_eui	the unique identifier of the end device
lorawan.f_cnt	the frame counter value of the uplink
lorawan.frequency	the frequency of the channel used (same as the field 'frequency')
lorawan.message	the category of message transmitted
lorawan.modulation	the modulation scheme used for transmission
lorawan.net_id	the network identifier
lorawan.spreading_factor	the spreading factor value used for transmission
payload_length	size of the payload
rssi	the received signal strength indicator of the transmission
snr	the signal to noise ratio of the transmission

Table 3.1: gateway_uplink data description

Table 3.2 describes the fields observed in the gateway_downlink dataset. This dataset consists of all downlink messages which were sent to end devices by the gateways. A different frame counter is used for downlinks. This value is recorded in the *lorawan.f_cnt* field in the dataset. Downlink can also be categorized into 3 types of messages - *JOIN_ACCEPT* (the message sent in response to a *JOIN_REQUEST* if the device is joining the network), *UNCONFIRMED_DOWN* (a downlink which does not require an acknowledgement), and *CONFIRMED_DOWN* (a downlink which requires an acknowledgement). The *power* field describes the transmission power the gateway has to use to transmit the message.

Field	Description
name	component name and message type
time	timestamp at gateway when message was sent
frequency	frequency of the channel used to send the message
id	unique identifier of the gateway
lorawan.airtime	computed time taken to transmit one frame
lorawan.bandwidth	bandwidth to be used for the transmission
lorawan.coding_rate	coding rate to be used for the transmission
lorawan.dev_addr	the device address allotted to the end device
lorawan.f_cnt	the frame counter value of the downlink
lorawan.frequency	the frequency of the channel to be used (same as the field 'frequency')
lorawan.message	the category of message to be transmitted
lorawan.modulation	the modulation scheme used for transmission
lorawan.net_id	the network identifier
lorawan.spreading_factor	the spreading factor value used for transmission
payload_length	size of the payload
power	transmission power used by the gateway

Table 3.2: gateway_downlink data description

Table 3.3 describes the fields in the gateway status dataset. The dataset consists of periodic Uplink messages describing the status update sent from the gateways. Gateways have varying periodicity. This contains the gateway position as measured by the on-board GPS module (if the gateway has one) or the manual coordinates entered on the TTN console by the gateway owner.

Field	Description
name	component name and message type
time	timestamp at gateway when message was sent to network
altitude	altitude of the position of the gateway
id	unique identifier of the gateway
latitude	latitude of the position of the gateway
longitude	longitude of the position of the gateway
message	the category of message transmitted

Table 3.3: gateway_status data description

The data structure of the Broker and the Handler is exactly the same and the uplink message structure is described in table 3.4. As described earlier, in the gateway_uplink dataset, *lorawan.dev_addr* is available for data messages and *lorawan.dev_eui* is available for request to join the network. The Broker is responsible of mapping the non-unique device addresses to the unique device by performing a series of MIC checks and provides this data in the *dev_eui* field for every message. The message categories are the same as those described for table 3.1. It is responsible for the de-duplication of messages, as a message can be received by several gateways. The Broker also checks for replay attacks by keeping a check on the Frame Counter value.

Field	**Description**
name	component name and message type
time	timestamp at gateway when message was received
app_eui	unique identifier of the application
app_id	identifier of the application
dev_eui	unique identifier of the device
dev_id	identifier of the device
gateway_id	unique identifier of the gateway
id	unique identifier of the component (broker or handler)
lorawan.airtime	computed time taken to transmit one frame
lorawan.app_eui	the unique identifier of the application for which the message is intended
lorawan.coding_rate	coding rate used for that transmission
lorawan.dev_addr	the device address allotted to the end device
lorawan.dev_eui	the unique identifier of the end device
lorawan.f_cnt	the frame counter value of the uplink
lorawan.message	the category of message transmitted
lorawan.modulation	the modulation scheme used for transmission
payload_length	size of the payload

Table 3.4: broker_uplink and handler_uplink data description

The downlink data structure for the Broker and Handler is described in table 3.5. The category of messages is similar to that in 3.2 however does not include $JOIN\_REQUEST$. The fields prefixed with the keyword *option* describe the fields that are defined by the downlink configuration selected. 2 downlink configurations are created by the Router, one for each of the receive windows. A score is calculated for each of these configurations. The Broker selects the best option from the scores calculated by the Router. The field $option.field$ consists of the score value of the option selected.

Field	Description
name	component name and message type
time	timestamp at component when message was received
app_eui	unique identifier of the application
app_id	identifier of the application
dev_eui	unique identifier of the device
dev_id	identifier of the device
gateway_id	unique identifier of the gateway
id	unique identifier of the component (broker or handler)
lorawan.dev_addr	the device address allotted to the end device
lorawan.f_cnt	the frame counter value of the uplink
lorawan.message	the category of message transmitted
option.deadline	deadline for preparation of a Downlink message by application
option.frequency	channel to be used for the transmission
option.identifier	identifier of the component (broker or handler)
option.lorawan.airtime	ccomputed time taken to transmit one frame
option.lorawan.coding_rate	coding rate used for the transmission
option.lorawan.modulation	the modulation scheme used for transmission
option.power	the transmission power
option.score	the calculated score for the selected option
payload_length	size of the payload

Table 3.5: broker_downlink and handler_downlink data description

3.2 External Data used

To aid with observing impact on and by the surrounding environment, external datasets were used and these will be described in this section.

3.2.1 Geographical Data

To observe gateway placement around the world, and to compute the number of gateways present in each country, I required a dataset containing boundary information of every country in the world to be able to locate and place gateways inside the country based on latitude and longitude coordinates. This boundary information is called a shapefile and is obtained from [32]. It is a binary file, and is read into python using the $fiona$ and the *geographicalpandas* libraries.
As this thesis specifically focusses on the performance of the network in the Netherlands, I required specific information regarding the shapefile of the different provinces in the country and their population densities. This data

was retrieved from [33] and [34].

3.2.2 Weather Data

In chapter 4, I have analysed the effects of weather and climatic conditions on how the network behaves in the Netherlands. To observe this, I required data on weather conditions in different parts of the country which I obtained from [35]. This dataset consists of recordings from 51 weather stations located all over the country. The locations of all these weather stations is provided in the form of coordinates which can be used to determine the closest weather station to every gateway to retrieve the most accurate information. The recordings are taken at every hour, and are displayed as such. A description of the data and explanation of the weather elements is available in table 3.6.

Weather Element	Description
DD	Vector mean wind direction in degrees (360 = north, 90 = east, 180 = south, 270 = west, 0 = calm)
FH	Vector mean wind-speed (in 0.1 m/s)
FF	Wind speed (in 0.1 m/s) averaged over the last 10 minutes of the last hour
FX	Maximum wind gust (in 0.1 m/s)
T	Temperature at 1.5m above surface (in 0.1 degree Celsius)
T10	Temperature at 10cm above surface (in 0.1 degree Celsius)
TD	Dew point temperature at 1.5m above surface(in 0.1 degree Celsius)
SQ	Sunshine duration calculated from global radiation (-1 for <0.05 hour)
Q	Global radiation (in J/cm^2)
DR	Precipitation duration (in 0.1 hour)
RH	Daily precipitation amount (in 0.1 mm) (-1 for <0.05 mm)
P	Air pressure at sea level (in 0.1hPa)
VV	Horizontal visibility during observation (0 = less than 100m, 1 = 100-200m, 2 = 200-300m, ..., 49 = 4900-5000m, 50 = 5-6km, 56 = 6-7km, 57 = 7- 8km, ..., 79 = 29-30km, 80 = 30-35km, 81 = 35-40km, ..., 89 = more than 70km)
N	Mean daily cloud cover (in octants, 9 = sky invisible)
U	Daily mean relative atmospheric humidity (in percent)
WW	Weather codes as explained in http://bibliotheek.knmi.nl/scholierenpdf/ weercodes_Nederland
M	Fog, 0 = not occurred, 1 = occurred in the previous hour and/or during the observation
R	Rain, 0 = not occurred, 1 = occurred in the previous hour and/or during the observation
S	Snow, 0 = not occurred, 1 = occurred in the previous hour and/or during the observation
O	Storm , 0 = not occurred, 1 = occurred in the previous hour and/or during the observation
Y	Ice formation, 0 = not occurred, 1 = occurred in the previous hour and/or during the observation

Table 3.6: Description of all weather elements

Chapter 4

Data Analysis and Insights

4.1 Traffic Analysis

The NOC data described in chapter 3 is processed and analysed to observe behaviour of LoRaWAN traffic and draw insights into the causes for various characteristics and improvements to the performance of the network. The data analysis procedure and insights are presented in this chapter. Previously, similar traffic analysis was performed by Blenn and Kuipers in their paper [36], where they observed the behaviour of TTN from data retrieved in 2016. In this chapter, I have also detailed comparisons with the results from [36], to observe changes to the network since the last traffic analysis.

4.1.1 Traffic Distribution

In a LoRaWAN, there are mainly 2 types of traffic - uplink traffic and downlink traffic, with the uplink traffic being more prevalent. The distribution of this traffic gives an indication of the traffic model resulting from a LoRaWAN. The traffic distribution helps us understand how to manage resources more efficiently to meet the demands of the quality of service and also stay within the limits of resource availability. The uplink and downlink traffic from the network is aggregated using bins of width $1s$. As seen in figures 4.1 and 4.2, usage of a $1s$ wide bin results in a chaotic distribution with no obvious distribution model. On average, for the uplink model, around 100 messages are received per second, and for the downlink model, around 10 messages are received per second. The downlinks make up approximately 9% of the total number of messages in the network.

Another observation from figures 4.1 and 4.2 is that downlink peaks and dips in traffic occur at the same time as corresponding traffic load in the uplink distribution. This means that the downlink traffic is triggered by the uplink packets i.e., the uplink messages require an acknowledgement or require the network to take some action.

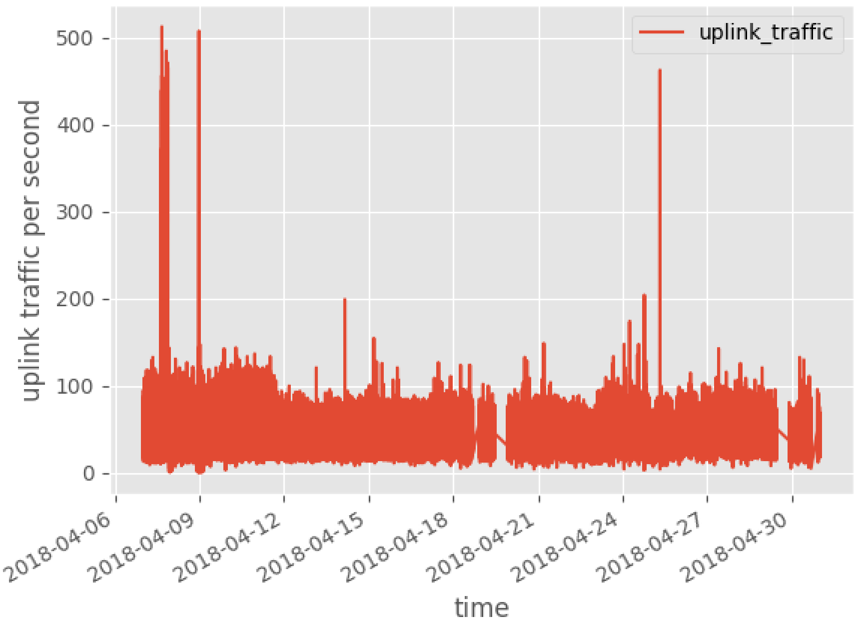

Figure 4.1: Uplink traffic distribution aggregated on 1s wide bins

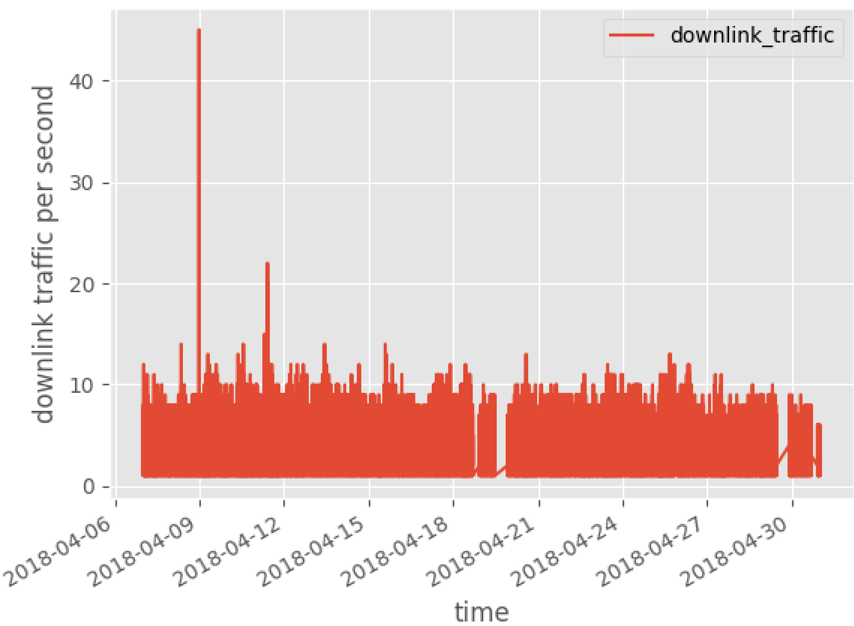

Figure 4.2: Downlink traffic distribution aggregated on 1s wide bins

4.1.2 Periodicity

By measuring the frequency at which devices send messages, we can make predictions about the future usage and further help with modelling the network. However, currently the applications on The Things Network are under development and it is extensively used for testing devices and gateways. Hence, periodicity analysis will not result in comprehensive results regarding application usage. Regardless, I computed the cumulative distribution of periodicity which can be viewed in figure 4.3. This graph shows that approximately 80% of the devices sent messages periodically, as the variation in period is 0 for cumulatively 80% devices. The rest of the devices send frames at periods with a standard deviation of 1.5.

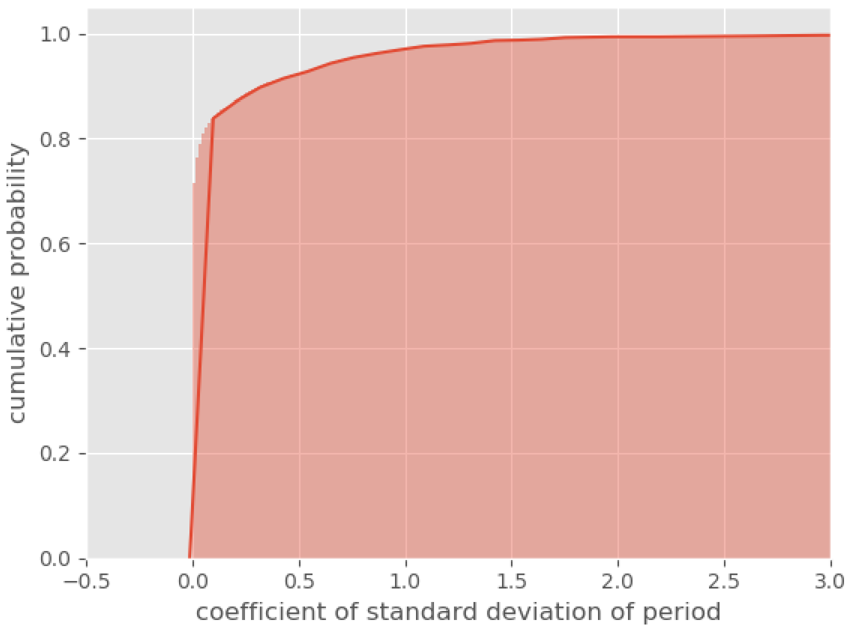

Figure 4.3: Cumulative distribution function of periodicity of devices

4.1.3 Signal Strength

Another important factor to measure the performance and behaviour of the network is to evaluate the signal strength which can be defined by 2 parameters - the Received Signal Strength Indicator (RSSI) and the Signal to Noise Ratio (SNR). The RSSI describes the power of the radio signal received and the SNR described the ratio of this signal power to the background noise. The probability distribution of these parameters of the received packets is

shown in Figure 4.4. In the RSSI distribution, 2 peaks with very close probability are observed. It is deduced that this distribution comprises of a mixture of 2 distributions with different location, scale and size parameters. The peaks are for the approximate values of -100 and -60. The lower the RSSI value, the further is the device from the gateway. Hence, due to the presence of multiple peaks, it can be deduced that there is almost the same distribution of devices at varying distances from gateways. On observing the SNR distribution, we see that there is a single peak at a SNR of approximately $10dBm$ with a tail extending into the negative side of the graph.
The peak on a positive SNR value indicates the presence of devices close to the the gateways. This also indicates that the path from the device and gateway is less noisy i.e., in open environments, over water bodies etc. However when RSSI and SNR are compared, the RSSI displays a higher possibility of a device to be further away from the gateway.

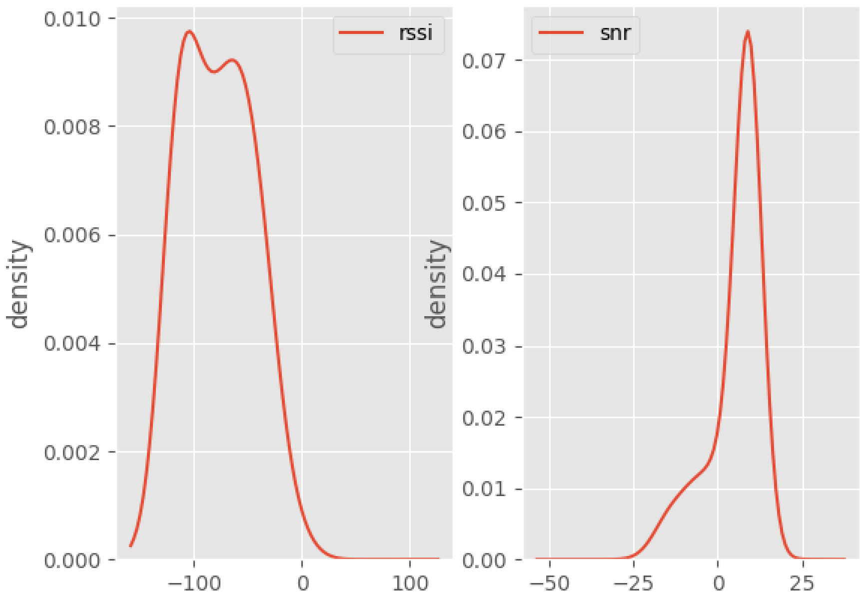

Figure 4.4: The probability density functions of the RSSI and SNR of uplink traffic.

This analysis was also performed in paper [36], and the results are available in figure 4.5. On comparing the results in figure 4.4 and 4.5, there are 2 peaks observed in RSSI in both, however, in 4.5, the peaks are observed at a higher value, indicating that the devices were closer to the gateway at the time when the data was recorded. The peak in SNR values is observed around the same value in both cases, however the left tail of the peak is heavier in the case of 4.4, indicating that there are devices further away from the gateway or the path from the device to the gateway has more disturbances. This comparison provides 2 possible changes to the network:

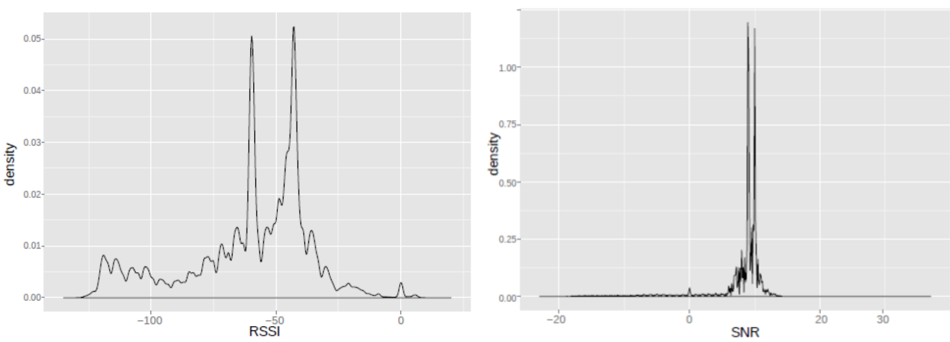

Figure 4.5: The probability density functions of the RSSI and SNR of uplink traffic performed in [36].

- An increase in the number of devices further from gateways, which is unlikely as the density of gateways is growing.
- An increase in the density of the network in more urban areas where the path loss will be higher.

4.1.4 Gateway Diversity

In LoRaWAN, packets can be received by multiple gateways. The number of gateways that receive a packet from a device is called the gateway diversity of the device. The measurement of this parameter is performed, as using triangulation to localize a device requires a message to be received by 3 or more than 3 gateways. Further, this parameter gives an indication of the redundancy of messages in the network. Redundancy is important in a network as lost packets at one gateway are received at another gateway increasing the Data Extraction Rate (DER) value and improving network performance - the DER value quantifies the number of packets received on the network as a ratio of the number of packet sent. As only one instance of a message has to be sent to the application, the Broker in the TTN performs de-duplication using the md5 sum of the hash key of the payload. In the current implementation, the de-duplication time is set to $200ms$, as the average measured delay between the first and last duplicate message is approximately $100ms$.

I measured the gateway diversity for each device in each application using the Broker database by counting how many unique gateways received a unique packet from a device in every application. A histogram displaying this measurement is seen in Figure 4.6 and table 4.1 shows some statistics of the receiver diversity. Messages from almost 24% of devices are received by 3 or more than 3 gateways, implying that these 24% devices have the ability to be localized using a triangulation algorithm. Only 55.43% of the devices are received by a single gateway, which shows that the network has improved in redundancy; by increasing the range of packet transmission, increasing receiver sensitivity or/and increasing the density of gateways. Messages from 2.2% of the devices are received by 10 or more than 10 gateways, with the highest gateway count for a device being 98.

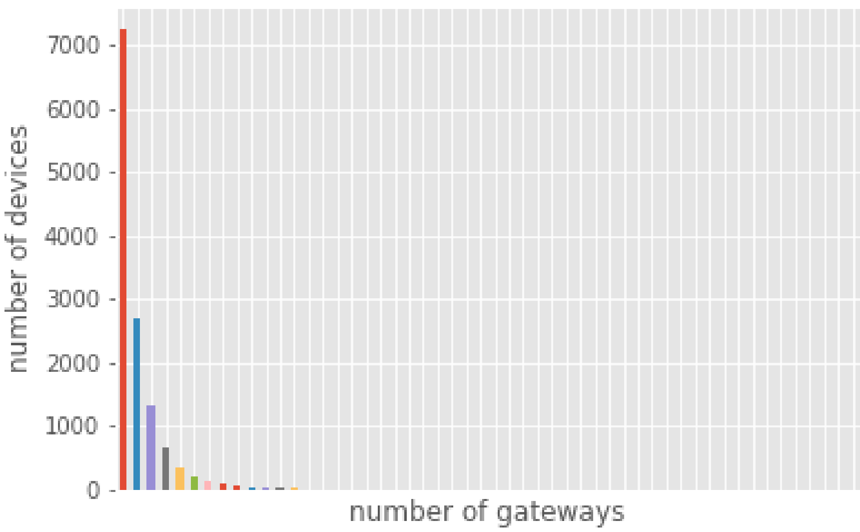

Figure 4.6: Histogram of receiver diversity

Number of Gateways	Percent of Devices
1	55.43%
≥ 2	44.57%
≥ 3	23.97%
≥ 10	2.2%

Table 4.1: Receiver diversity of gateways

Similar gateway diversity analysis was also performed in [36] and the results are shown in table 4.2. In the dataset used for this analysis, the highest number of gateways that received frames from the same device is 31.

On comparing results from tables 4.1 and 4.2, it is clearly evident that the diversity of gateways has increased either due to an increase in the gateway density or due to improvements in the transmission parameter selection enabling messages to travel further and hence be received by more gateways. This feature is exploited to develop an ADR model as is shown in chapter 5.

Number of Gateways	Percent of Devices
1	94.8%
2	3.7%
3	1.1%

Table 4.2: Receiver diversity of gateways as shown in [36]

4.1.5 Device Usage

The network grows as the number of devices in the network increase as the end-devices make up the most populous element. Getting an idea of the usage of these devices i.e., the number of packets sent and frequency of transmission, would help with modelling the network and predicting the ideal placement for gateways to optimize the DER.
First, I looked at the usage of individual devices. This was done by performing a double aggregation on the device count to retrieve the number of devices that sent n number of packets. It resulted in a skewed distribution which is displayed in a log scale and resembles a power law model with coefficient 9.78. This distribution is displayed in figure 4.7, left. This figure implies that the majority of the devices sent very few packets, a major reason being the duty cycle restrictions placed on the devices using the licence-free spectrum.

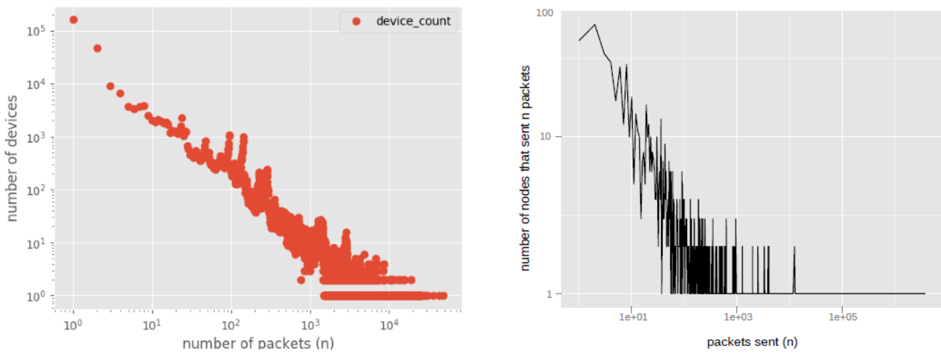

Figure 4.7: Device Usage

Similarly, the analysis was performed in [36]. The result of the analysis is shown in figure 4.7, right, which also shows a power law trend in the usage of devices.

4.1.6 Data Rate Distribution

A critical parameter in the performance of a LoRaWAN is the Data Rate used for transmission. Data Rate is made of 2 parameters - the spreading factor and bandwidth as explained in section 2.2.8. Analysing the distribution of using different data rates for traffic further helps with modelling LoRaWAN traffic and creating optimized models for data rate adaption. The traffic is filtered to remove the Join-Request messages, as Join-Requests are default to particular data rates. In the EU868 ISM band the default data rate is set to DR9.

As observed from figure 4.8, left, majority of the traffic uses SF7, which is

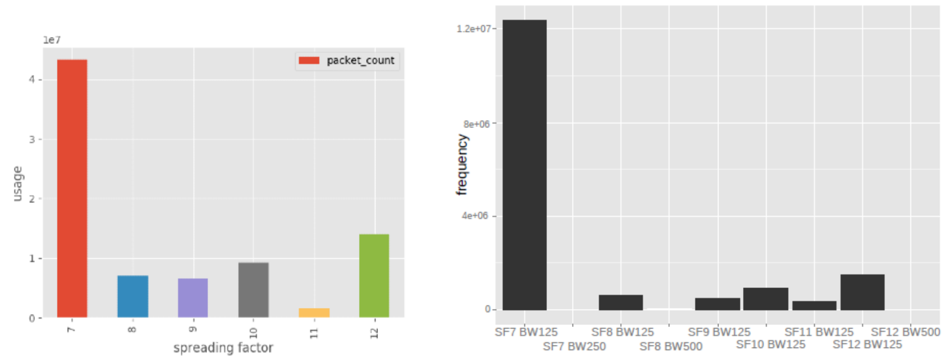

Figure 4.8: Spreading Factor Distribution

the highest data rate and has the lowest airtime, hence using the least power for transmission. However, for successful transmission with SF7, the environment conditions need to be close to ideal, with less noise or the device closer to the gateway.

The spreading factor distribution in [36] was observed and a histogram showing the trend is shown in figure 4.8, right. Similarly, SF7 is the most widely used, however in the later analysis, other spreading factors are used more frequently, especially SF12. As the higher spreading factors are used for longer range of transmissions, the range of the network has increased. However, the higher spreading factors are still not used to their full capacity, leaving room for improvement in the number of simultaneous transmissions. This is another factor explored for exploitation in the ADR model developed in chapters 5 and 6.

The data rate distribution and performance with each data rate is also performed in chapter 5.

4.1.7 Frequency Channel Use

Unlicensed radio frequency channel bands are used by LoRaWAN. In Europe, this is the EU868 frequency band which has a range of from 863MHz to 870MHz. Since, in this thesis I have focussed on analysing LoRaWAN performance in Europe, specifically, the Netherlands, I only analyse packets using the EU868 for transmission, which is described in section 2.1.2. The use of these channels is orthogonal and uplink transmissions on all 9 channels can be received concurrently. First, I analysed the use of these channels for only the payload frames (as Join-Requests by default use the 868.3 or 868.5 channels. This distribution can be seen in figure 4.9, left.

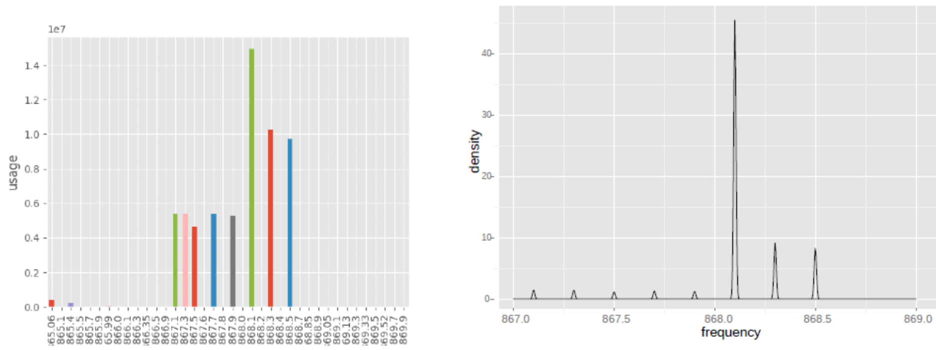

Figure 4.9: Frequency sub-channel Distribution

From this histogram, we observe that 868.1, 868.3, and 868.5 are used the most often. The channel 867.5 is also used by RFID tags in Utrecht, causing the channel to be less available for use in the area.
The frequency sub-channel usage distribution is also seen in paper [36] and the histogram of usage can be seen in figure 4.9, right. Similar to figure 4.9, left, the 868.1, 868.3 and 868.5 channels are used most often, however the usage has become more evenly distributed in the later analysis. There is potential for improving the capacity with the current distribution and this is the main factor utilised in improving the performance of the network which is analysed and discussed in chapter 5.

Further concentrating on Netherlands, I analysed the frequency channel usage per province. More detailed province-wise analysis is done in section 4.2. I normalized the usage of each channel in each province and this is seen in Figure 4.10.

As observed from this figure, in Groningen, the use of the 868.3 channel is the most prevalent and this is the only province where traffic is not distributed amongst the channels and is concentrated on a single channel. This will be further analysed in future chapters.

4.2 Gateway Analysis

Gateways are a crucial element to a LoRaWAN as they form the connection between devices and the network. As the density of gateways increase, the network becomes more connected with lesser packets being dropped, more devices connecting to the network and an increase in redundancy in the network.
I have mapped out TTN gateway locations all over the world and plotted a heat map displaying the density of gateways all over the world seen in figure

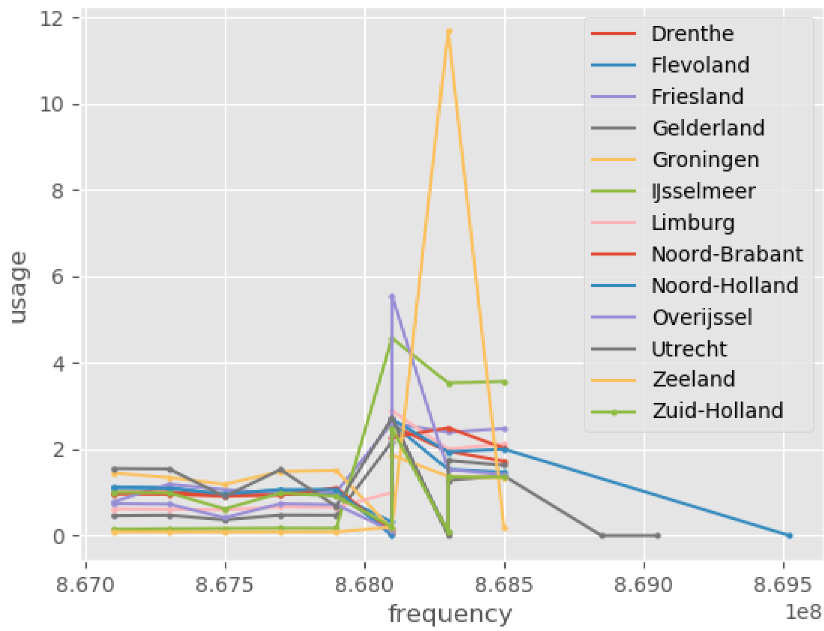

Figure 4.10: Netherlands province-wise frequency distribution

4.11. Approximately one-fourth of all the gateways in the world are located in the Netherlands.

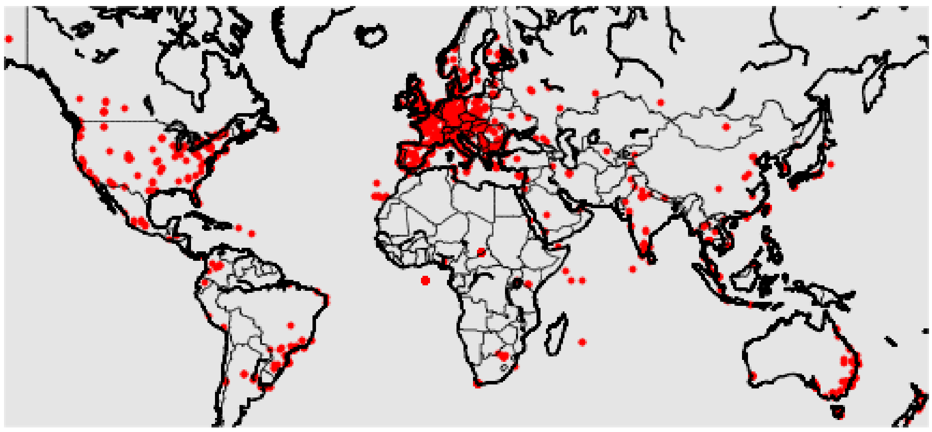

Figure 4.11: Gateway locations over the World

Focussing on The Netherlands, I plotted heat maps for gateway density per province in the country in figure 4.12. Utrecht has the highest gateway density, followed by North Holland and South Holland. The lowest gateway density is observed in Friesland and Zeeland.

To observe the degree of urbanism on gateway placement, I used popula-

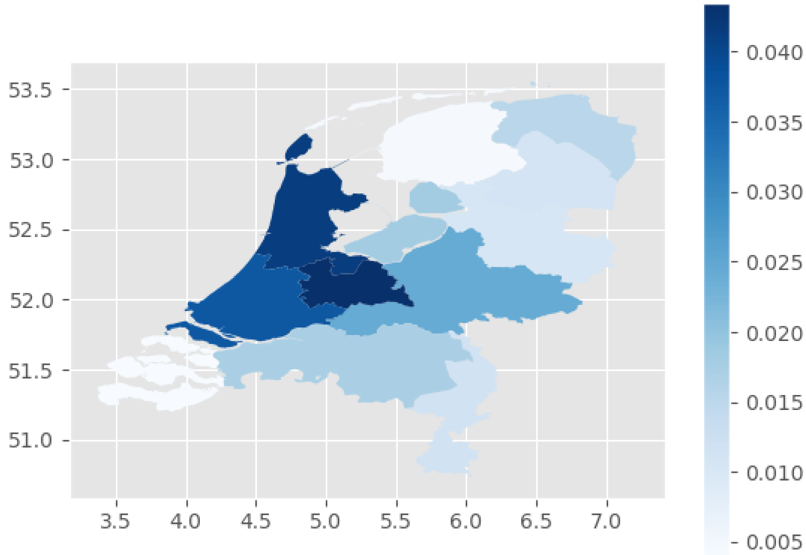

Figure 4.12: Province wise gateway density heat map

tion density to quantify it. A heat map consisting of the population densities per province is observed in figure 4.13. The red dots indicate locations of gateways. From this graph, South Holland has the highest population, whereas, the Northern provinces have the lowest densities. On comparing the results seen in figures 4.12 and 4.13, there is not a direct correlation between the population density and the number of gateways, as the least populated Northern provinces also have a significant density of gateways.

On taking the reciprocal of the gateway density, we can compute the area covered by each gateway. A comparison of this value with the population density is shown in figure 4.14.

Gateway placement impacts the performance of the network. Placing more gateways in device dense areas, or areas with high traffic flow, can improve the DER, as more gateways implies that their presence is in closer proximity to devices.

4.3 External Environment Impact

As the Netherlands has a very flat and even terrain, it creates the ideal scenario for analysing the effects of environmental conditions like the climate and weather. To perform this analysis, I've used the data that was described

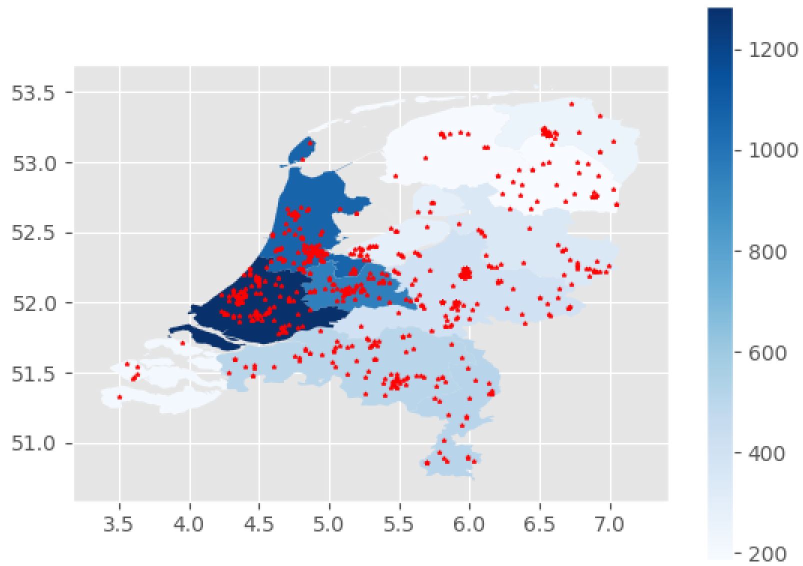

Figure 4.13: Province wise population density with gateway locations

in section 3.2.2. On reading the work done by Luomala et. al. in [37], in which they had observed an impact on RF signals due to humidity and temperature, I attempted to recreate their analysis on LoRaWAN signals.

Static Gateway Extraction

Some gateways are placed on moving objects such as vehicles, and are constantly moving. If the gateway has a GPS module, the gateway can be programmed such that the location is automatically read from the GPS and sent as meta-data on frames. If the gateway does not have a GPS module, it is the responsibility of the user to update the location of the gateway in the TTN console. Only static gateways should be considered for any analysis regarding impact of external influences as this analysis is performed over an extended period of time and moving gateways will cause changes in the environment around the gateway.
As some gateways use GPS read coordinates, the values of longitudes and latitudes can vary slightly, hence the standard deviation is computed and gateways with variation below 0.01 are considered static.

First I looked at the short term effects on the signal strength between a stable device-gateway link. This results in observations to visualize the

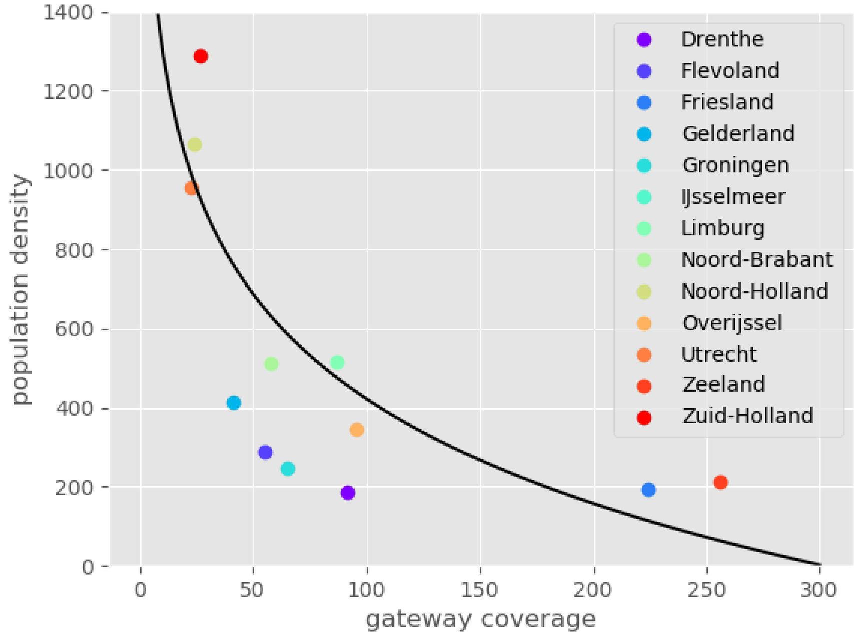

Figure 4.14: Coverage of gateways per province

difference caused due to the changes in environment due to day and night variation over a time period of 24 hours. The variation in temperature and humidity over a period of 24 hours is recorded and compared with variation in RSSI in figure 4.15. The RSSI varies positively with humidity and negatively with temperature, showing a direct correlation with the 2 factors. This feature should be explored in further detail in the future to make adjustments for climatic conditions to improve network performance.

Next, I observed the effects of long term variation, over days with climatic changes in figure 4.16. However, since the LoRaWAN data used for the analysis in this case has been collected over the month of April, the climatic conditions are consistent and don't vary as much as the difference between summer and winter months as is considered in [37]. The correlation between the 2 graphs shown in figure 4.16 is negligible and computed to be -0.07.

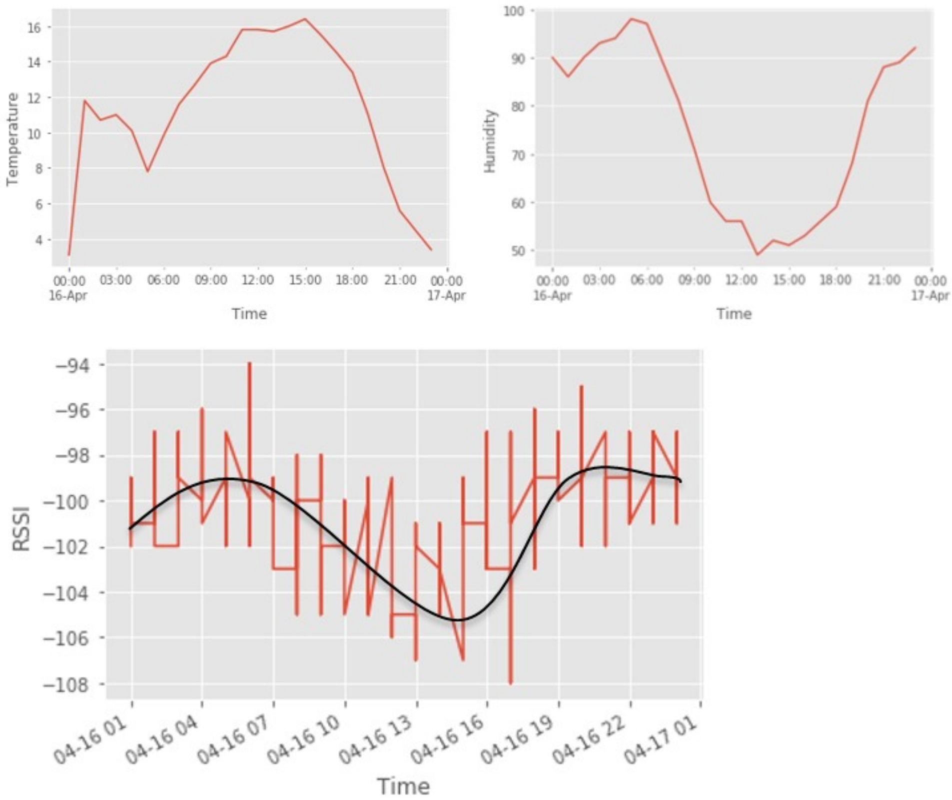

Figure 4.15: Effect of temperature and humidity on RSSI

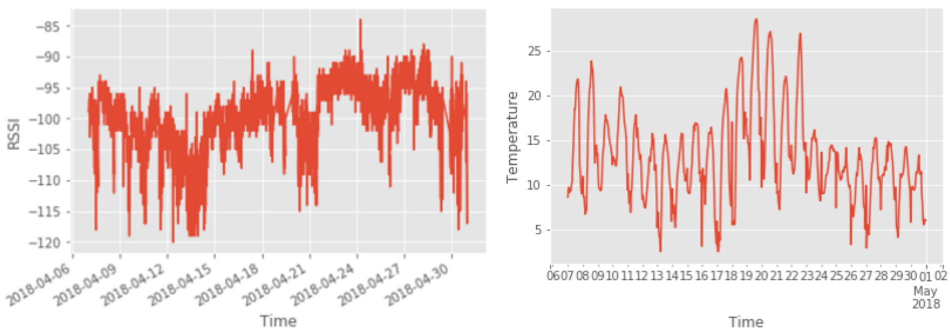

Figure 4.16: Effect of temperature and humidity on RSSI - Long term

Chapter 5

ADR Tracking and Performance Analysis

To optimize the ADR model, it is important to analyse the behaviour of the current implementation as this will provide an insight into the performance and the various causes for impact on performance.

5.1 Data Extraction for Analysing ADR Behaviour

As mentioned in section 2.2.9, an ADR model requires that the devices that implement it are immobile. This ensures that the link quality remains constant during the execution of the algorithm which uses historic information.

5.1.1 ADR Devices Information Extraction

To analyse behaviour of the current implementation of ADR, the devices on which ADR is active have to be extracted. The steps seen in figure 5.1 are followed for this. First, the static links are to be extracted from the gateway uplink dataset. From section 4.3, the location of gateways at every uplink is known and static gateways located in the Netherlands are obtained. Mobile devices do not move for long periods of time and the ADR can be applied to them during this time. Hence, over the 1 month time period, I extricated the devices per day which have an active ADR by iterating through the database and extracting devices which showed an increase in the data rate. On performing this extraction, I found 318 device-gateway links to track ADR behaviour.

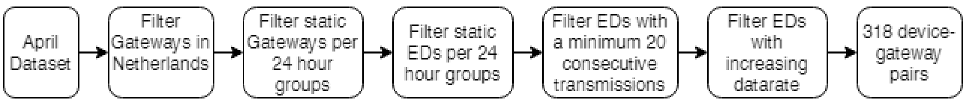

Figure 5.1: Data extraction procedure for ADR devices

5.1.2 Relevant Information Extraction

For every device and gateway link where the ADR model is implemented, the gateways also receive frames from other devices in the vicinity. Further, the gateways also send downlink frames when required to devices. These transmissions make the gateway busier and could cause the gateway to miss transmissions from the ADR devices, causing performance depreciation, i.e., a decrease in the DER value. The busyness of the gateway is an important factor which affects the performance of the ADR device. To be able to compute the busyness of gateways, the relevant transmissions from gateway_uplinks and gateway_downlinks have to be compiled.
In attempts to be consistent with the computation effort in the algorithm described in section 2.3.2, and use historic information from the last 20 ADR uplink frames, the information regarding the busyness and frequency channel usage is extracted from the non-ADR traffic during the time-frame of the 20 ADR uplinks.

Figure 5.2: Data extraction procedure for relevant transmissions

5.2 Parameters for Analysing ADR Behaviour

Every time the ADR is activated, causing data rate to increase in the filtered set of device gateway links, a history of uplinks is recorded and analysed. As described in section 5.1.2, there are 2 sets of historic uplinks recorded -

- The first belongs to the device on which the ADR is active. The uplinks are grouped in counts of 20, to maintain a similar structure of storage and computation as the current implementation of ADR. In all future mentions, this device will be referred to as the ADR_device.

- The second set consists of uplinks sent by all other devices to the gateway from the first set. The second set is extracted for every group of 20 uplinks using the corresponding time-frame of the groups.

The following parameters are defined and computed to decide initial conditions and the following ADR methodology. These parameters cover the extent of analysis in this thesis, as they define performance evaluation of the device and are readily available as meta-data in the transmissions.

5.2.1 Gateway Busyness

The gateway busyness factor defines the availability of the gateway to receive transmissions from the ADR_device, and takes into account the number of uplinks it receives from non-ADR_devices, number of downlinks sent via the gateway and the number of different devices it is transmitting to and from. In the case of ADR_devices which have a gateway diversity of more than 1, the percentage of frames out of 20 uplinks by the ADR_device received by the gateway are taken into consideration. Hence to quantify busyness of a gateway, the following model is developed shown in equations 5.1 and 5.2.

$$busyness_{multi-diversity} = (UL\_count + DL\_count)\left(\frac{ADR\_frame\_count}{20}\right)\left(\frac{1}{gw\_diversity}\right) \tag{5.1}$$

$$busyness_{single-diversity} = (UL\_count + DL\_count) \tag{5.2}$$

In equations 5.1 and 5.2, UL_count and DL_count refer to the number of uplinks and downlinks received on and sent by the gateway, $gw\_diversity$ refers to the number of gateways that receive the frames from the ADR_device, and ADR_frame_count refers to the count of the number of frame received during the last 20 uplinks from the ADR_device on the gateway in question. A gateway is considered 'busy' if the computed busyness value is non zero. It is considered 'non-busy' if the computed busyness is zero.

5.2.2 Data Extraction Rate

The DER of a device indicates its performance in terms of the number of frames that are dropped in transit. Computing the DER (from equation 5.3) helps decide whether performance improvement is required and is the most useful parameter in visualising performance improvement after modifying the ADR model.

$$DataExtractionRate = \left(\frac{ADR\_frame\_count}{20}\right) * 100 \tag{5.3}$$

A DER_Threshold is defined by the user, depending on the requirements of the application, to set the performance expectations of the network.
The DER for each ADR_device is computed, regardless of the gateways that receive the frames, for every group of 20 transmissions. If the DER is sufficiently high, i.e., crossing the DER_Threshold, the uplink reception is already efficient. In this case, the transmission is made resource efficient by optimising the use of data rates and transmission power.
If the DER value for a device is lower than the DER_Threshold, the DER variation is analysed against the gateway diversity of the device and its frequency channel usage to find room for performance improvement. This helps define the decisions the model makes in varying conditions.

5.2.3 Frequency Channel Usage Distribution

Frequency channels are orthogonal and different channels can be used for multiple simultaneous transmissions. Uneven usage of frequency channels can be modified to improve performance depending on the requirement of the initial conditions.
For both sets of historic traffic recorded, the frequency channels used are aggregated. The historic traffic from the ADR_device informs us about the usage of frequencies by that device. The historic traffic consisting off all competing uplinks informs us about the availability of frequency channels. On performing comparisons between these aggregations, if required, the frequency channel can be modified using the channel mask (chMask) field in the LinkADRReq MAC command. It is recommended to provide at least 2 frequency sub channels in the channel mask, so that if one channel becomes unavailable, the other channel can be utilised for the transmission.

5.2.4 Link Quality

In the current implementation of ADR, the SNR is the only parameter used to vary the data rate and power. In the implementation developed in this thesis, the link quality is to be included with the other factors described above to make comprehensive decisions on the modification of transmission parameters. As described in section 2.3.2, the NStep variable defines a threshold for link quality. When NStep is greater than 0, the link quality is good and is tolerant to data rate increase and transmission power decrease. When this value is less than 0, the link quality is not sufficient for the transmission and the transmission power is amped up. A similar comparison is used in this implementation to quantify link quality.

5.3 Analysing ADR behaviour

The main objective in this section is to evaluate traffic history at the time when ADR is triggered based on the parameters described in section 5.2, also briefly described below:

- The number of packets received as a ratio of the number of packets sent by the device (DER).
- The amount of traffic being received on the gateway from other devices, i.e., the busyness of the gateway.
- The frequency channel usage and distribution by the device and the other devices sending frames to the same gateway.
- The signal quality of the device-gateway link (this is the only factor considered in the currently implemented ADR on TTN).

Analysing the behaviour of these factors when the ADR model is triggered helps us quantify the performance of the network in the current implementation, and provides insights into the potential areas of improvement. The model developed in this thesis mainly focusses on increasing the DER of the device through manipulation of the transmission parameters.
There are 2 main considerations while performing the analysis and developing the model -

- To evaluate if costly resources (transmission power and datarate) can be restricted based on the performance and link quality of the transmission.
- To evaluate the availability of frequency channels to

For the purpose of this analysis and model development, I have considered the DER_Threshold as 80%, i.e., 80% of the frames sent by the device are received successfully. This value depends on the requirements of the application and should be set by the user.
First the devices are split into 2 categories depending on the gateway diversity - single diversity and multiple diversity. Out of the total number of devices implementing the ADR model, 174 of the devices have a gateway diversity of 1, and 109 devices have gateway diversities of more than 1, resulting in 318 unique device gateway links.

5.3.1 Results of Analysis - Single Diversity Devices

This section describes the behaviour as per the analysis parameters for devices with single gateway diversity.

Step 1: DER Filter

The first step is to filter devices-gateway links for which the calculated DER is more than the threshold for every computation. In the dataset consisting of single diversity gateways, the number of links that are always above the DER_Threshold is 117 out of 172. The rest of the links consist of instances where the DER is to be improved.

Step 2: NStep Derivation

The quality of the signal is quantified using the value called NStep as described in section 2.3.2 to decide resource constraining on the device. On computing the NStep value following the method used in the SemTech recommended algorithm, 99% of the cases resulted in a positive NStep, causing an aggressive increase in data rate and decrease in transmission power. This is due to the usage of the maximum SNR of 20 uplinks to compute the SNR_margin. The analysis for these 2 sets of devices is performed in

sections 5.3.1 and 5.3.1.
The NStep value has to be made stricter for signals with low quality, by modifying the NStep threshold. The figure 5.3 compares the variation in mean DER and SNR values with NStep from the available data. For NStep of 3, the average DER crosses 80% (which was earlier set as an experimental threshold), and the average SNR crosses 0.

Hence, the NStep threshold for single diversity devices is set to 3.

For values above 3, the device undergoes resource restriction, and under the value of 3, undergo resource slackening, if required on the basis of performance.

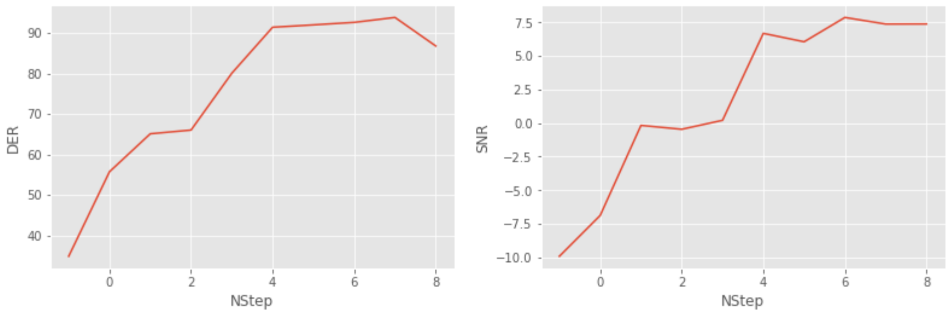

Figure 5.3: NStep thresholds for Average DER and Average SNR (single diversity)

Case Analysis 1: Satisfactory DER

For the devices with a DER of more than 80%, the resources can be constrained, depending on the signal quality measure, NStep, which according to the threshold derived from figure 5.3, is more than or equal to 3. The mean SNR is 7.94 for these devices, is a satisfactory value of signal quality for performance. In this case, the resource utilisation is made efficient by increasing the data rate and decreasing the transmission power, the specific model used to do so is described in chapter 6.

Case Analysis 2: Unsatisfactory DER and Busyness = 0

There are 25 cases making up 17.8% of total traffic observed where the ADR_device is the only device sending messages to the gateway, and the busyness is a value of 0 for these gateways. Hence, interference from other devices is not a cause of performance degradation in these cases. The main reason is the inefficient usage of transmission parameters, of which the frequency channel usage is analysed here.

Frequency Channel Usage

In this section, the variation in frequency sub channel usage by the device is observed by analysing this transmission parameter used by the ADR_device.

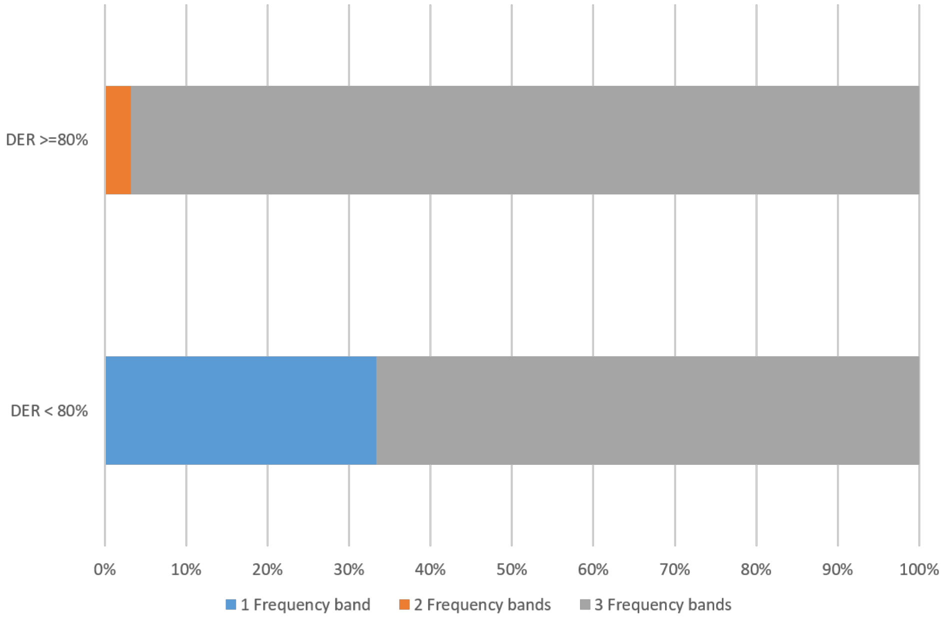

Figure 5.4: Frequency band usage for different DER thresholds

As seen from figure 5.4, when the DER is below a threshold of 80% (accounts for 7.5% of traffic), 33.3% of the devices have a single frequency band available and 66.7% of the devices have 3 frequency bands available. In the case of DER equal to or above 80% (92.5% of traffic), every device has at least 2 frequency bands available, with majority of the devices using 3 sub-bands.

3 frequency bands should suffice for satisfactory performance.

Below the DER_Threshold, the performance degradation occurs in the devices which only have a single frequency band available for use, the average DER in this case is 27% and average SNR is -2.06. Hence the method to improve performance is to modify the channel mask such that more channels are allotted to the device, and increase the transmission power of the device.

<u>Case Analysis 3: Unsatisfactory DER and Busyness != 0</u>

The ADR_devices where there are interfering devices sending frames to the same gateway make up approximately 82% of the total traffic using 22 devices. The average SNR for devices with a DER below 80% is -1.44

(accounting for 37% of traffic) and for those above or equal to 80% is 6.65 (63% of traffic).

Busyness Analysis

The interference from other devices sending frames to the gateway causes the gateway to be busy; the busyness factor as calculated from equation 5.2 is on average 62 for devices with a DER below the threshold and 50 for devices with DER above the threshold. For a busyness of above 55, the average DER is 79.2%, hence a maximum busyness of 55 can be tolerated by devices.

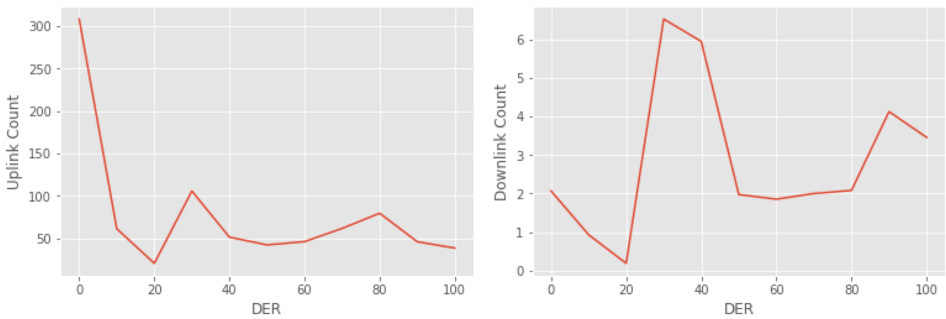

Figure 5.5: Uplink and Downlink variation for DER

As busyness consists of a count of interfering uplinks and downlinks, these are separately analysed to observe the effect of direction interference and is seen in figure 5.5. The count of uplinks and downlinks is averaged for DER widths of 10%, and the count of uplinks decreases with an increase in DER, demonstrating a performance degradation due to a higher number of uplinks being received on the gateways. However, the downlink count does not display any trend, and is dismissed from future analysis due to the comparatively low number of downlinks sent by the gateway. The busyness equations in 5.1 and 5.2 are rewritten without the downlink transmission count as seen in equations 5.4 and 5.5.

$$busyness_{multi-diversity} = (UL\_count)(\frac{ADR\_frame\_count}{20})(\frac{1}{gw\_diversity}) \quad (5.4)$$

$$busyness_{single-diversity} = UL\_count \quad (5.5)$$

Frequency Channel Usage

The next factor addressed for these devices is the usage of frequency bands. For the devices with a DER below 80%, an increasing of average DER is noticed with an increase in the number of frequency bands used by the device in the last 20 uplinks from figure 5.6. This shows a dependency on the number of frequency channels used by each device for the performance.

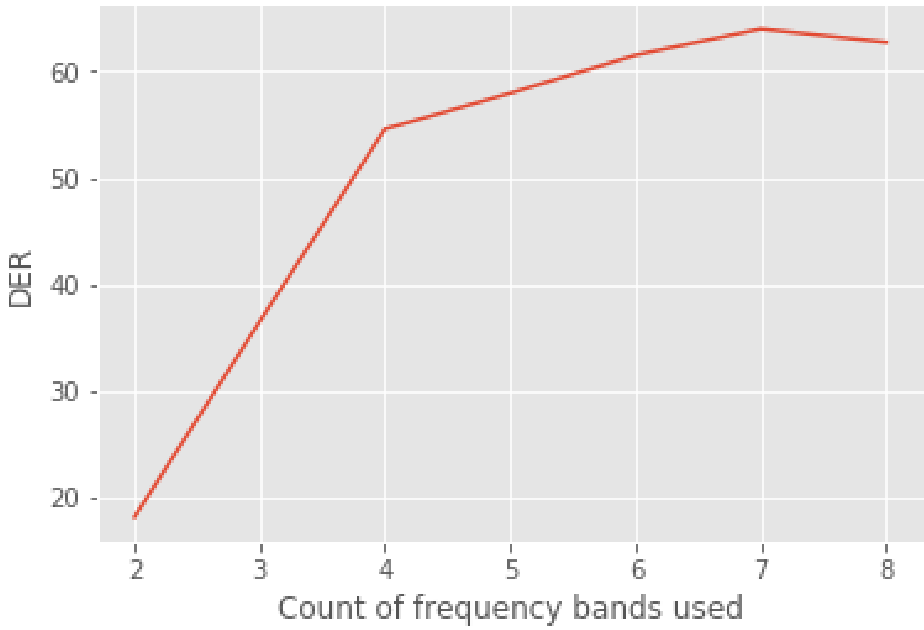

Figure 5.6: Trend in average DER for varying count of frequency bands

To determine the required number of frequency bands at which satisfactory performance is achieved, the average DER is analysed for all the devices (under and over 80% DER) with the number of frequency bands. This is extracted from the dataset. A peak in the performance, with an average DER of 93%, is observed when the number of frequency bands used is 3, showing that using the right 3 bands can provide sufficient resources for the device to perform as per required.

Selection of 3 frequency bands is sufficient to provide the required performance.

I have computed the variation in distribution of the frequency channels, and for under-performing devices, the average standard deviation reduces as the DER increases, i.e, when the variation in frequency band usage is high and the frequency bands are not used evenly. This trend can be seen in figure 5.7.

The more evenly the frequency channels are used, the better is the measured performance of the device.

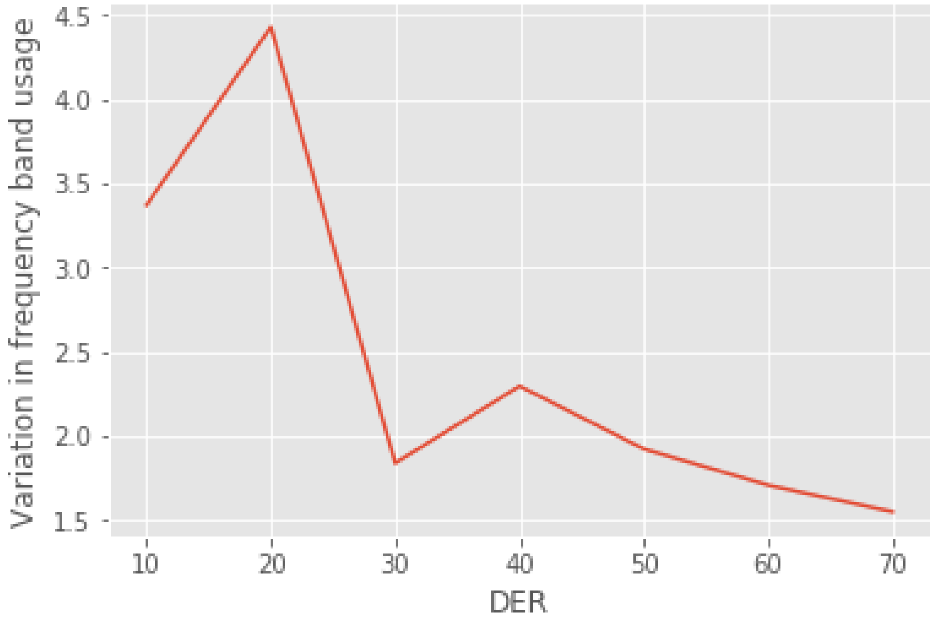

Figure 5.7: Trend in average frequency band distribution for varying DER

To determine the frequency channels that are the most free to be used, for all the non ADR interfering devices, the frequency channels used over the last 20 uplinks are recorded and the least used frequency channels are compared with the frequency channels used by the ADR device. As seen from above, 3 frequency channels are sufficient to provide the required DER. The least used 3 channels are set to be used by the device through the channel mask as will be explained in detail in section 6.1.1.

5.3.2 Results of Analysis - Multi Diversity Devices

This section discusses the devices from which frames are received on multiple gateways.

Step 1: Nstep Derivation

Similar to the single diversity analysis, the trends in average DER and SNR values are compared with NStep, to observe how the variation in signal quality affects the signal. This is shown in figure 5.8. From the figure, at a value of NStep = 4, the DER crosses the assumed threshold of 80% and the SNR crosses 0.

Hence, for multi diversity gateways, the threshold for signal quality measurement is taken as 4.

Above the determined threshold, the resources are to be constrained and below which, the performance is to be improved.

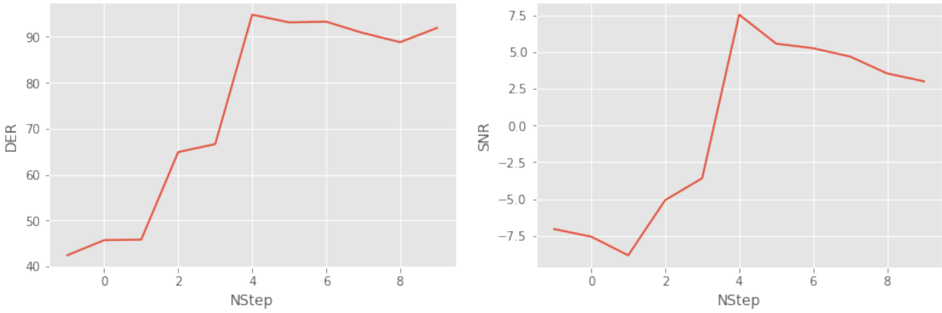

Figure 5.8: NStep thresholds for Average DER and Average SNR (multi diversity)

Step 2: Gateway Diversity Variation

There are 4 different gateway diversity values observed from the dataset - the percentage of traffic on each gateway diversity is shown in table 5.1. It is clearly seen from the table that most of the devices have a gateway diversity of 2. The traffic on gateway diversity of 8 is high because each message is being received by up to 8 devices, and causing a comparatively larger number of frames to be recorded.

Gateway Diversity	% of traffic
2	52.7
4	1.9
7	2.6
8	42.8

Table 5.1: Percentage of traffic on different gateway diversities

As the bulk of traffic is on gateway diversity 2 and 8, I separately analyse the effect of number of uplinks and downlinks from other devices on the DER. The trend variation for a gateway diversity of 2 is seen in figure 5.9, where the DER is grouped for every 10%. For higher DER's the number of uplinks reduces.

Busyness of a device with gateway diversity of 2 is mainly impacted by messages in the uplink direction.

For devices with a gateway diversity of 8, figure 5.10 demonstrates the variation in uplink and downlink count with an increase in DER. As there are 8 gateways available to each devices, the dependence on the number of uplink transmissions reduces as the redundancy is high.

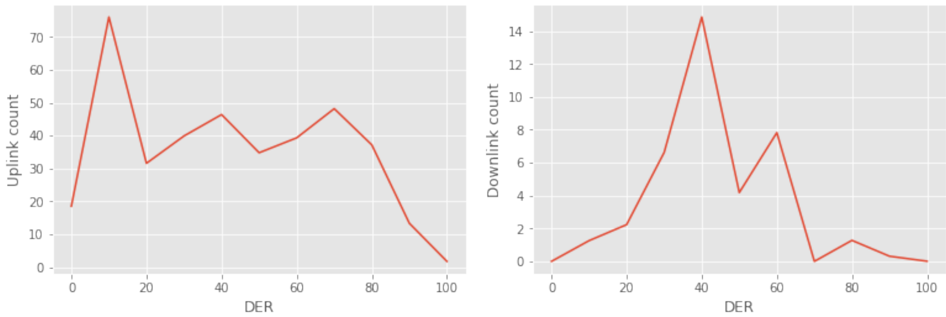

Figure 5.9: Uplink and Downlink variation for DER's of devices with gateway diversity 2

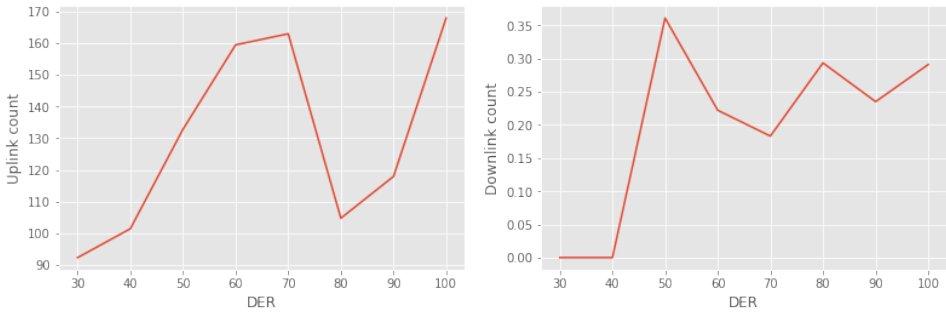

Figure 5.10: Uplink and Downlink variation for DER's of devices with gateway diversity 8

Case Analysis 1: Unsatisfactory DER

Gateway Usage Analysis

The next step analysed is observing the individual usage of the gateway by the ADR_device during the 20 uplinks which are used to perform the analysis, and this is seen in figure 5.11. For devices with a DER of more than 80% and a gateway diversity of 2, 97.9% of uplink sets are entirely received on both gateways. When the gateway diversity is 8, 72.1% of uplink sets are entirely received on all 8 gateways.
When the DER is below 80%, for a gateway diversity is 2, 62.4% uplink sets are entirely received on both gateways; for gateway diversity of 8, 15.8% uplink sets are fully received on all gateways. Hence, when the DER is more than the threshold, the redundancy of messages is high enough to use resources more efficiently.

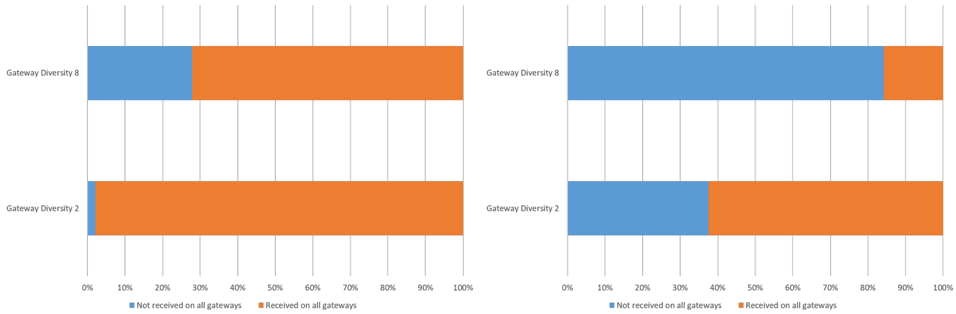

Figure 5.11: Gateway Usage for DER more than DER_Threshold (left) and DER less than DER_Threshold (right)

Busyness Analysis

Computing the busyness of each device, as defined in equation 5.1, and on averaging the busyness for every 10% bin of DER, it is seen for gateway diversities more than 4, the busyness increases as the DER increases. When there are more gateways receiving the message, the tolerance to busyness is higher. For the devices with a gateway diversity of 4 or lower than 4, the busyness reduces as the DER increases, showing the expected trend of devices having a poorer performance when the gateway is busy. These trends can be seen in figure 5.12.

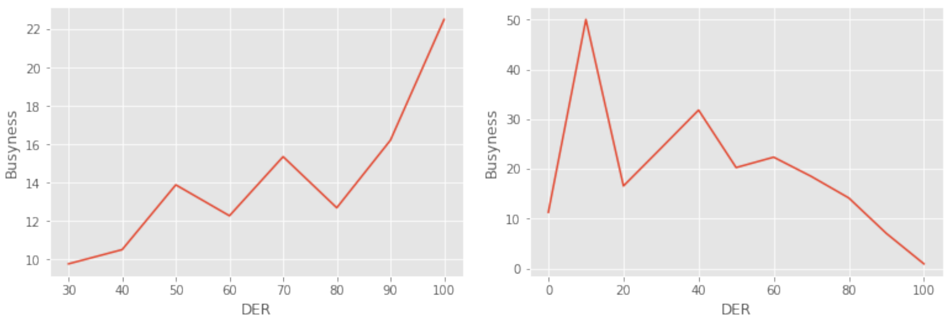

Figure 5.12: The busyness trend for devices with gateway diversity more than 4 (left) and less than 4 (right).

Using a gateway diversity of 4 as a threshold, the devices below and above are analysed separately as they display differing features.

Frequency Usage Analysis

The frequency band usage is observed next for these devices. The 2 different diversity groups are analysed separately, first looking at the devices with a gateway diversity of 4 and less than 4. As the number of different frequency bands a device uses during the last 20 uplinks increases, so does the DER (seen in figure 5.13, right). For a gateway diversity of more than 4, when 2 bands are used, the average DER peaks when the number of bands used is 3, showing that 3 frequency bands are sufficient to provide performance improvement.

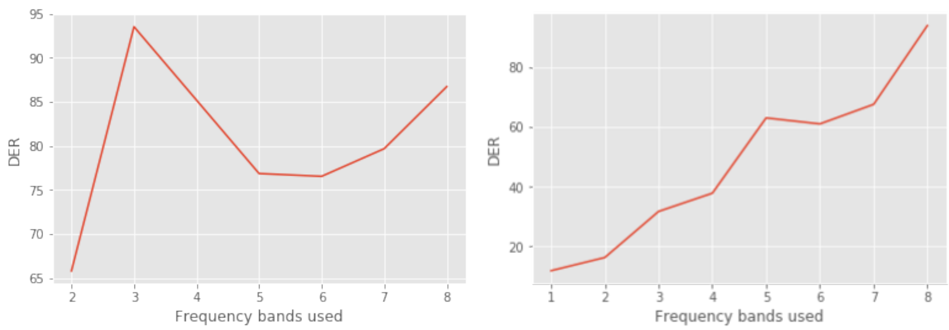

Figure 5.13: The variation in DER with frequency bands used for devices with diversity more than 4 (left) and less than or equal to 4 (right)

In both these cases, making more frequency bands available to the device will improve performance. However, when the gateway diversity is higher, lesser frequency bands are sufficient to reach the same performance level.

Case Analysis 2: Satisfactory DER

Previously, the NStep threshold for multi-diversity gateways was derived as 4. Hence, when the DER for the device is greater than the threshold and the computed NStep is greater than 4, the transmission undergoes resource constrainment. For these devices, sufficient performance is observed when 3 frequency channels are used, and the frequency channels used can be minimised, followed by the reduction of transmission power and data rate increase.
Using the results and derivation of thresholds from this section, an ADR model to improve the performance of the network is developed in section 6.1.

Chapter 6

ADR Model Development

After the extensive analysis seen in chapter 5, 2 ADR models are developed for optimising the performance - there are 2 separate models to differentiate between the devices with single and multiple diversity of gateways. The behaviour for these categorisations of devices is explained in chapter 5. This chapter proposes the ADR model and describes the effect of using the optimisation on the performance of the network through theoretical verification using the data.

6.1 Optimised Algorithm Proposal

In the previous chapter, from section 5.2, the factors to quantify features of traffic to design an optimised ADR model were developed using the datasets derived from gateway_uplinks and gateway_downlinks.
Devices with varying gateway diversity displayed different behaviour which was generalised in chapter 5. Due to this difference in traffic behaviour, 2 different models are developed and explained in the following subsections.

Datasets recorded

There are 2 datasets recorded to define transmission parameter modifications for the device on which ADR is to be implemented.

- **Historic ADR Traffic** The 20 uplinks recorded from the device on which ADR is implemented. This data structure consists of every copy of the frame received at every gateway (in the case of multi gateway diversity devices).
- **Historic Traffic** Uplinks recorded at the Historic ADR Traffic's gateway(s) from all other devices (excluding the device on which ADR is implemented) between the extreme timestamps of Historic ADR Traffic.

Initiation of ADR

Before the ADR model is initiated, the gateway diversity of the device has to be determined so that the corresponding algorithm is executed. As per the algorithm explained in section 2.2.9 and 2.3.2, as soon as the LinkADRReq-LinkADRAns exchange takes place, the meta-data of the next 20 uplinks is used to determine the modification to be made to the transmission parameters. Similarly, in the proposed model, the last 20 uplinks (Historic ADR Traffic) from the device are first used to determine the number of different gateways receiving the frames from the device, identified by the `gateway_id`. Following the segregation done on the basis of gateway diversity, the algorithm from figure 6.1 is applied on the device to classify based on initial measured performance.

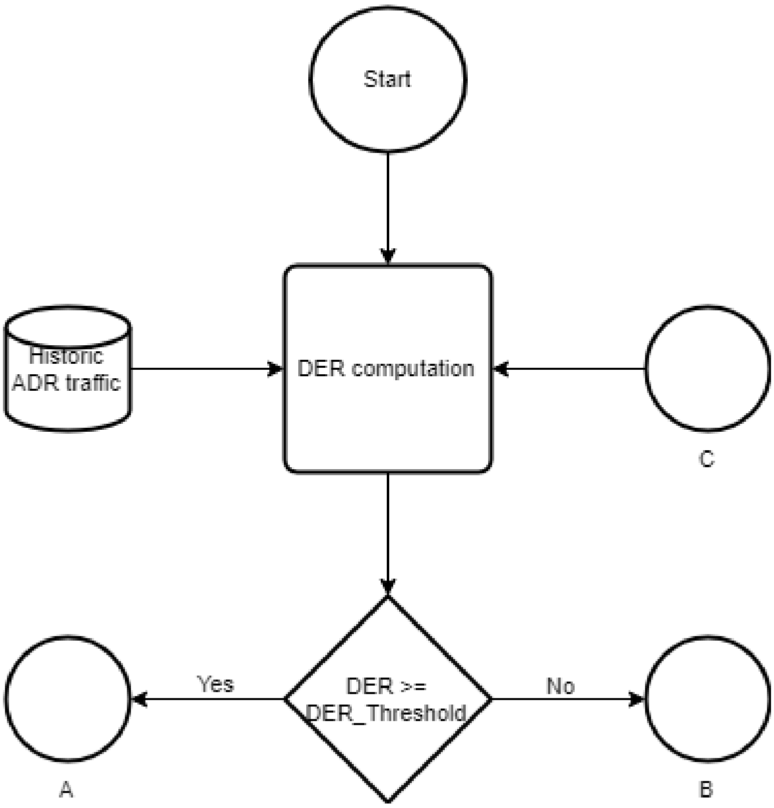

Figure 6.1: DER threshold selection

6.1.1 ADR model for Single Diversity Devices

The model developed for devices with single gateway diversity can be seen in figures 6.2 and 6.3. If the gateway diversity is 1, this model is activated. The first step is to check whether the performance during the last 20 uplinks is satisfactory according to the DER value computed from the Historic ADR Traffic dataset, and compared with the user defined requirement for performance (DER_Threshold) in figure 6.1.

Satisfactory DER (DER $\geq$ DER_Threshold)

In this case, the device does not require performance improvement, as the number of frames being dropped in transmission is less than the tolerance of the application. However, there are cases where the signal quality is such that the device is more tolerant to using less robust transmission parameters (i.e., higher data rates, lower transmission power and lesser number of frequency channels). To define the threshold for tolerance, a value called NStep is computed; this calculation is described in equations 2.7 and 2.8. As per the analysis performed in section 5.3.1, a threshold value of 3 is derived for NStep by looking at the trend in the average SNR value.

NStep $\geq$ 3

When the NStep value crosses the threshold, the device is tolerant to lower quality signal transmission. In this case, first the number of frequency channels is reduced one by one to a minimum of 3, as from section 5.3.1 it is seen that with 3 channels, the average DER is satisfactory. After removing the number of frequency channels, we need to assure that the performance has not been impacted. Hence, the DER is recomputed and the number of frequency channels are further reduced only if the newly computed DER is greater than or equal to 102.5% of the DER_Threshold.

If the number of frequency bands is 3 or less than 3 or the DER has reduced to below 102.5% of DER_Threshold, the next step is to increase the data rate and/or decrease the transmission power according to figure 6.5. After the resources are constrained, it is important to reconfirm that the DER value is still more than the DER_Threshold. Hence the next step leads back to the initial DER check in figure 6.1.

NStep $<$ 3

When the NStep value is less than 3, that means that the signal quality is lower than the threshold, however the system is performing well in these conditions and the algorithm is exited as no resources should be constrained in this case.

Unsatisfactory DER (DER $<$ DER_Threshold)

There are many cases where the gateway receives frames from and sends frames to other devices apart from the ADR device. This is quantified from the busyness value as computed in equation 5.2, using the Historic Traffic data set. The behaviour when the there are interfering devices varies from

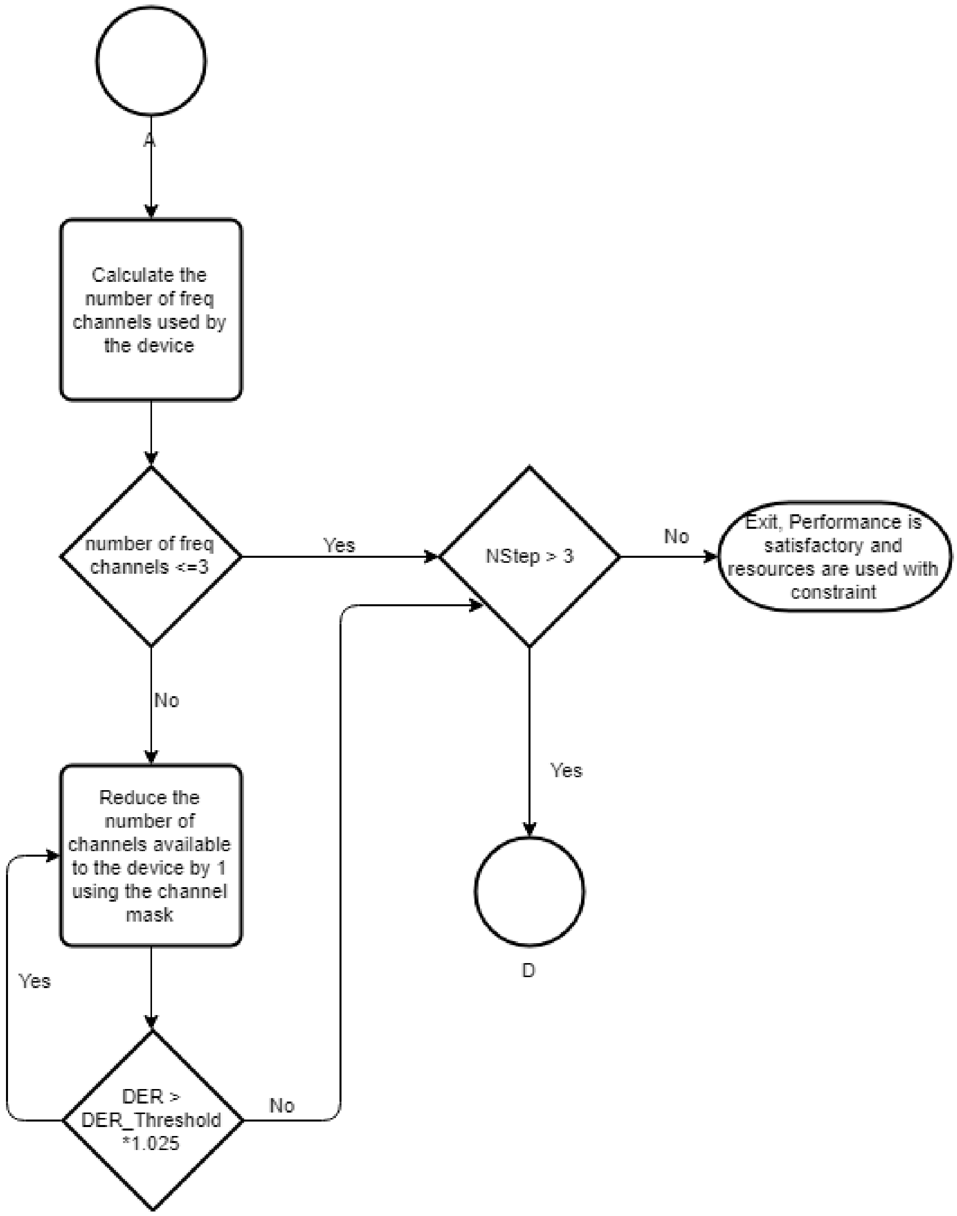

Figure 6.2: Single diversity model for satisfactory DER

the behaviour when there are no interfering devices. This model is seen in figure 6.3.

Busyness = 0
When the busyness value is 0, there are no other devices communicating with the corresponding gateway during the time period of the last 20 uplinks. Hence, the deterioration is not due to interfering devices

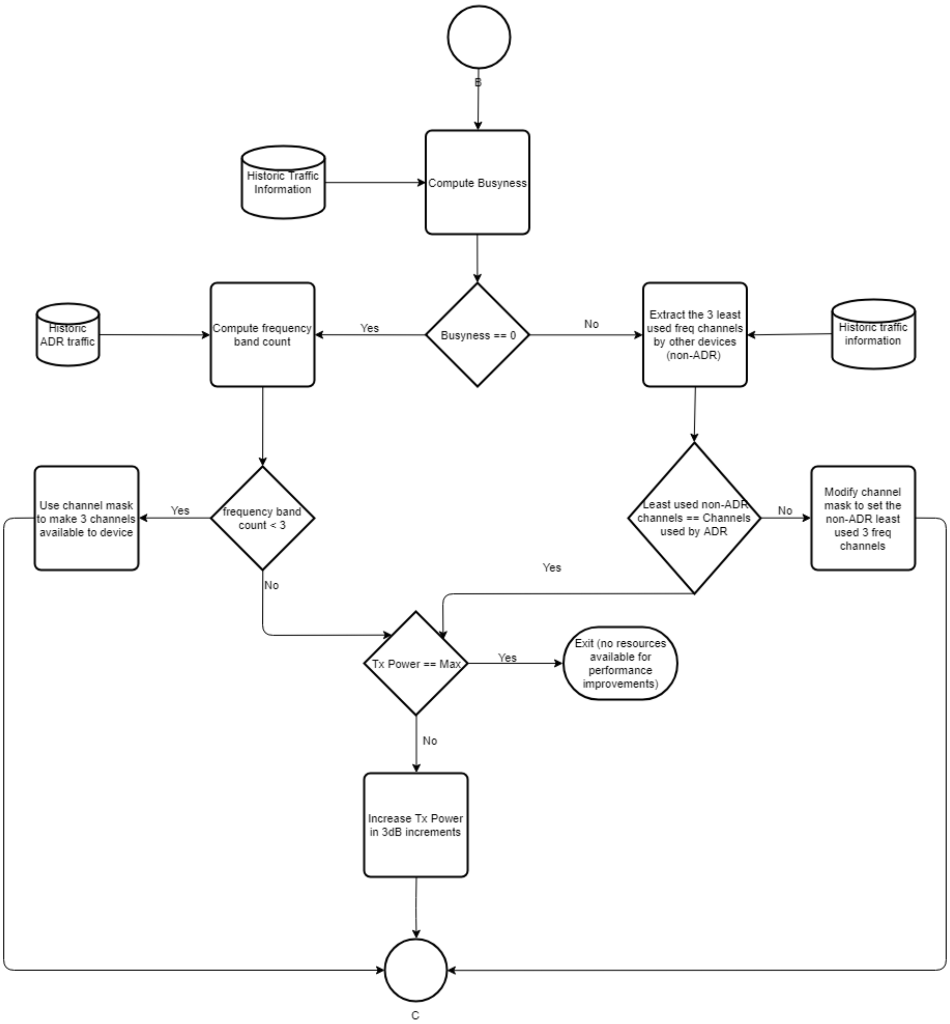

Figure 6.3: Single diversity model for unsatisfactory DER

or collisions. The frequency channels of the device are restructured to provide the right number of channels to use. When there are 3 channels used by the device, the DER is satisfactory, hence, if the number of channels used by a device is less than 3, 3 channels are allotted based on the most successful channels in the last 20 uplinks. The historic ADR traffic information is used for this part of the analysis. If the number of channels is 3 or more than 3, the transmission power is increased in increments of 3dB. After every increase in transmission power and change in channel mask, the DER threshold is checked. When the transmission power has reached the maximum value, there are no more resources left to use, and the device has reached its optimum performance and cannot be improved any further, the model is then exited.

Busyness > 0

When the busyness is greater than 0, there are other devices sending messages to the corresponding gateways. In this case, the frequency channels used by the other devices during the time period of the last 20 uplinks are also available as resources. Compiling a list of all the frequency channels used by the ADR_device and all other devices, the least used channels (by the other devices) are extracted. These channels are compared with the channels used by the ADR_device. If they are exactly the same, then the channel mask is not modified. For the cases where the channels are not the same, the channel mask is modified. Once the channels allotted to the device are the same as the 3 least used channels, the transmission power is increased in increments of 3dB, and the DER threshold check is performed. When the transmission power has reached the maximum possible value, the model is exited as no other resources are available for the device.

6.1.2 ADR model for Multi Diversity Devices

The ADR model for multi diversity gateways is presented in figures 6.4 and 6.6. 2 or more gateways receive frames from the ADR device. Similar to the single gateway diversity gateways, the DER is computed and compared with the threshold. DER computation uses the historic ADR traffic dataset as can be seen in figure 6.1.

Satisfactory DER (DER ≥ DER_Threshold)

Similar to the satisfactory DER case in the devices with single diversity, devices with this case do not require performance improvement. First, the frequency channel re-allotment is done. From the data analysis, a minimum of 3 channels are used to obtain the required performance. The number of channels are decreased one at a time if this count is more than 3. The decrease only occurs if the DER is maintained to be 102.5% of the threshold value.
The next step is to use the signal quality to decide the constrainment on the transmission parameters. From the data analysis in section 5.3.2, the threshold for NStep was found to be 4, above which the signal quality ensures that the device is tolerant to the use of less robust transmission parameters. Below the threshold, the device is able to provide the required performance.

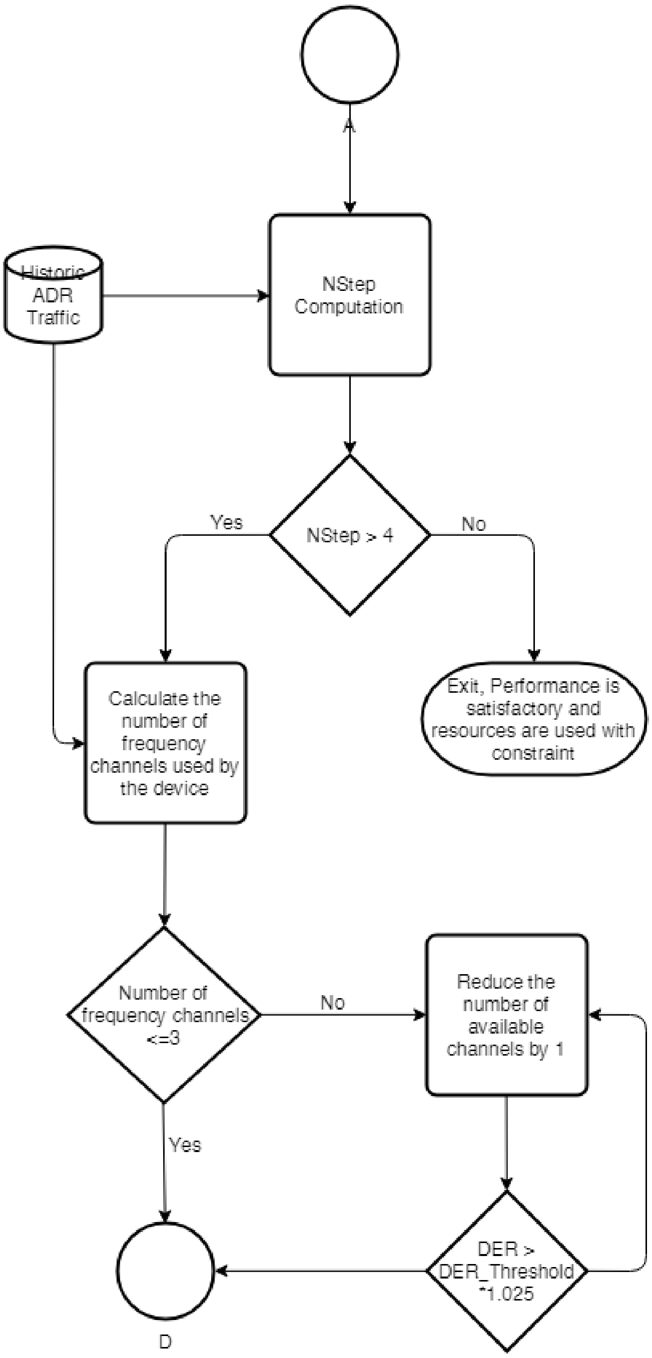

Figure 6.4: Traffic Optimised ADR model for multi gateway diversity devices when DER is satisfactory

NStep $\geq$ 4

In this case, the resources are constrained by decreasing the data rate and decreasing the transmission power as per figure 6.5. After every modification, the DER is checked with the threshold, and confirmed that it still satisfies the requirements.

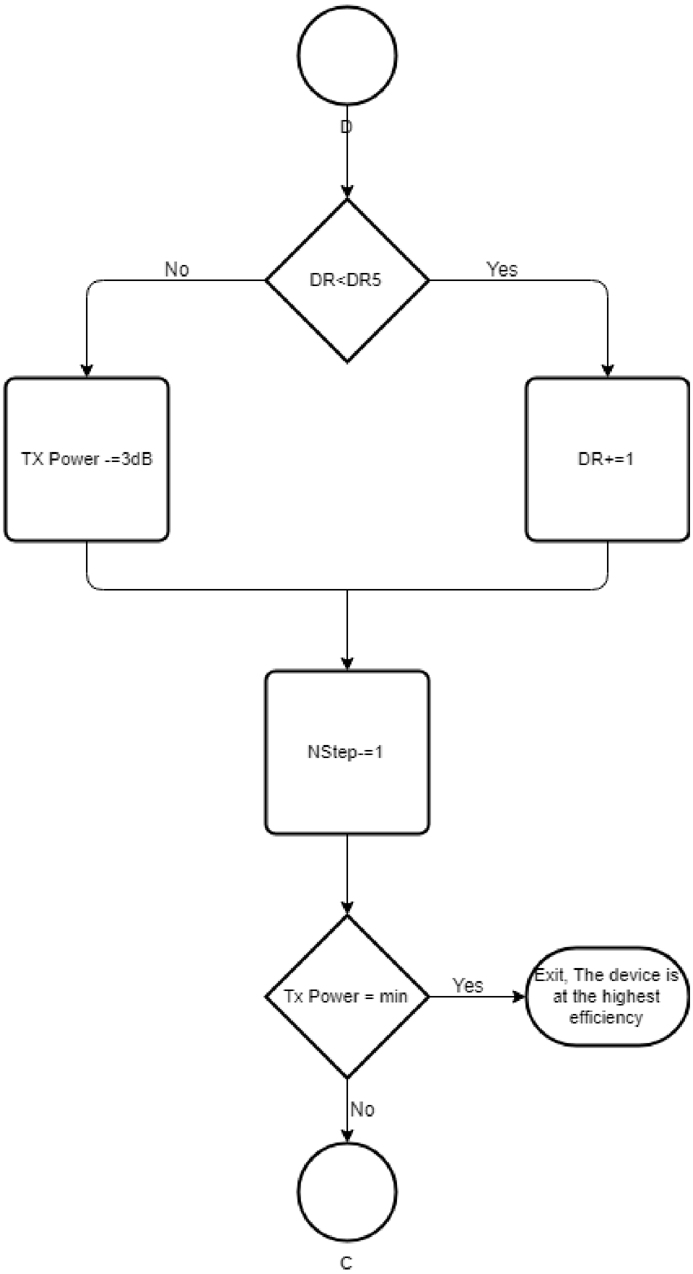

Figure 6.5: The resource constraining algorithm similar to the SemTech implementation

NStep < 4

In this case, the low signal quality results in satisfactory performance. No resource constraints regarding the signal quality are applied and the algorithm is exited.

Unsatisfactory DER (DER < DER_Threshold)

The devices with this behaviour need performance improvement. Devices with different gateway diversities have different behaviour. The gateway diversities vary from 2 to 8, and the distribution of the diversity count was analysed in section 5.3.2. With a threshold gateway diversity of 4, devices above and below are found to have different characteristics.

Gateway diversity > 4

When the gateway diversity is more than 4, the device performs satisfactorily on just 3 frequency channels. The 3 most available bands are computed using the historic ADR traffic and historic traffic and checked if out of all the available bands, the 3 least used bands by the non ADR devices are used by the device. If they are not, then these 3 channels are allotted to the device by modifying the channel mask. Once it is confirmed that the channels used by the device are the 3 most available ones, and if the DER has not improved, the transmission power is increased in increments of 3dB. Once the transmission power has reached the maximum possible value, the model is exited as there are no other resources available which can improve the performance.

Gateway diversity $\leq$ 4

For the devices with lower gateway diversities, the more the frequency channels available, the better the performance (DER) of the device. The number of frequency channels used by other devices (i.e., are available to the gateway) and the number of frequency channels used by the device are computed and compared. If the number of channels available are greater than the number of channels being used, the channel mask is modified such that the number of channels allotted to the device is increased in increments of 1, and the DER is checked after every increment. This continues till the channel mask is modified to allot the maximum number of frequency channels available. The next step is to increment the transmission power by 3dB step by step till the maximum is reached. The DER check is performed after every increment.

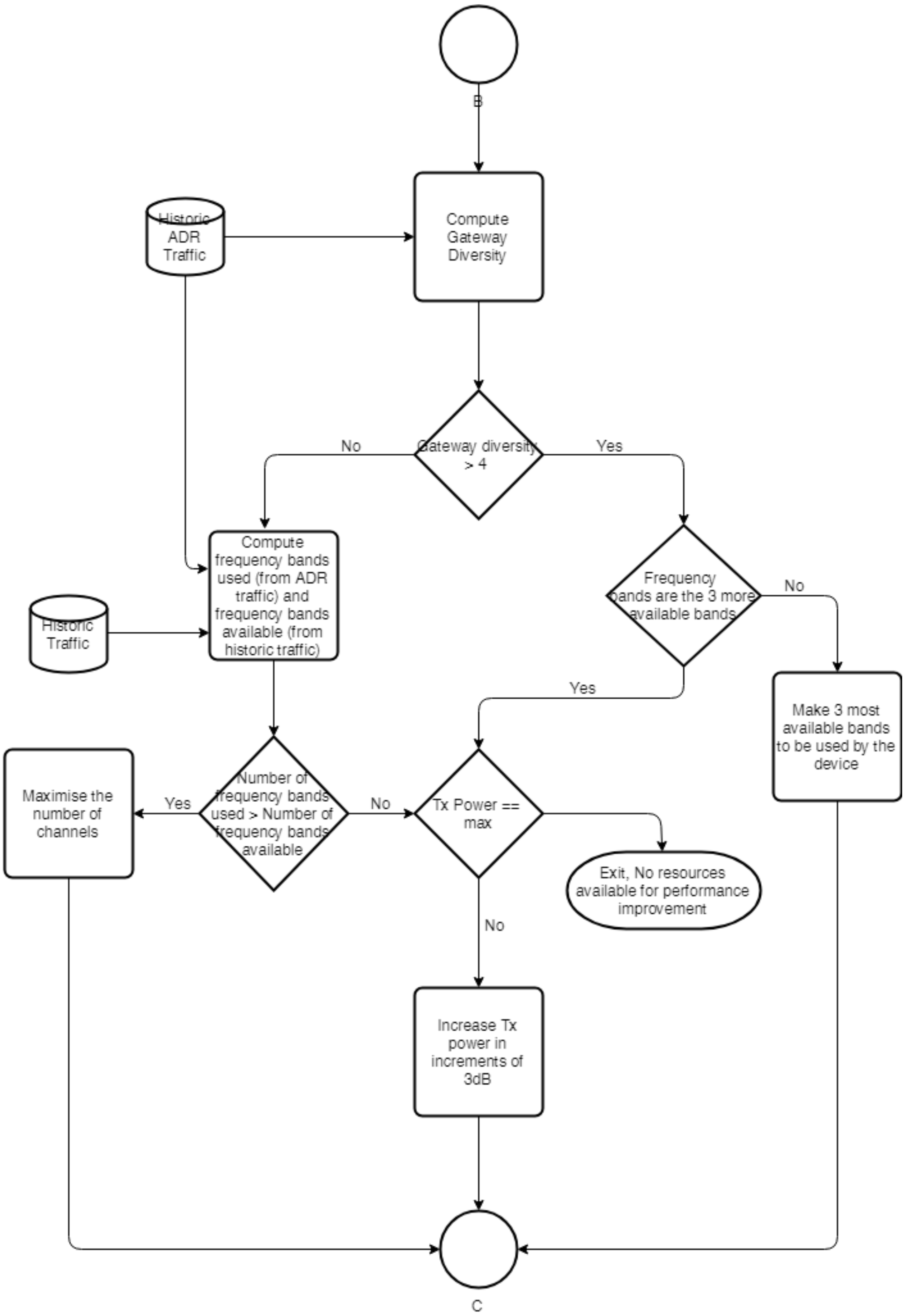

Figure 6.6: Traffic Optimised ADR model for multi gateway diversity devices when DER is unsatisfactory

6.2 Verification of Modified ADR using Data Processing scripts

To compare the working of the modified algorithm with the originally implemented ADR in TTN from section 2.3.2, data processing scripts are written which process the input data and transmission parameters from the TTN NOC and the results are compared. The results are modelled based on the available dataset. Every case, wherever possible and required, addressed in the modified ADR algorithm is accounted for and ran through the 2 processing scripts.
Similar to the development of the model in the previous section 6.1, this verification is split for devices with single and multiple diversity gateways. The gateway diversity of devices is not a factor considered in the Semtech recommended algorithm, hence for the following 2 cases, the diversity distinction is only taken into account for the model developed in this thesis.

6.2.1 Devices with Single Gateway Diversity

There are 7 cases addressed, as described in table 6.1. All these cases are in regards to devices with a gateway diversity of 1.

Case #	DER	Link Quality	Busyness	Nature of Frequency channels used
1	≥ 80	NStep > 3	N/A	Channel count ≤ 3
2	≥ 80	NStep ≤ 3	N/A	Channel count ≤ 3
3	≥ 80	N/A	N/A	Channel count > 3
4	< 80	N/A	$= 0$	Channel count < 3
5	< 80	N/A	$= 0$	Channel count ≥ 3
6	< 80	N/A	> 0	Identical channel usage
7	< 80	N/A	> 0	Non-identical channel usage

Table 6.1: Cases addressed for single gateway diversity devices

Case 1

In this case, the DER value is satisfactory, and the device does not use more than 3 frequency channels, which was described as the required number of frequency channels for the device to achieve satisfactory performance. If the NStep value is more than 3, there is room for improving the resource consumption and the devices in this situation undergo the modified resource constraining algorithm as seen from figure 6.5. This part of the algorithm is not modelled and verified as the exact same model is used in the original implementation.

Case 2

This is similar to the above case with the only difference being the NStep value less than or equal to the defined threshold of 3. Since there is no room for improving the resource consumption, the device is operating at maximum efficiency and the algorithm is ceased.

Case 3

In this case, the DER value is satisfactory, and the number of frequency channels can be constrained as described in 6.2 where the number of frequency channels are reduced one by one only if the DER is more than 102.5% of the DER_Threshold after every modification to the channel mask.
Once the DER is below 1.025*DER_Threshold, the model will proceed to the resource constraining model from figure 6.5. This part of the algorithm does not require verification as stated previously.
In the case of device with device address 26012183, as seen in figure 6.7, when the number of frequency channels used is reduced from 7 to 6, the DER of the device reduces from 86.9% to 83.3%. These values are more than the defined threshold. The DER then drops from 83.3% to 80% when the number of frequency channels are reduced further. Since the algorithm checks for the DER to remain more than 1.025 times the DER_Threshold (82%), it will ensure that the DER will not reduce below 80%.

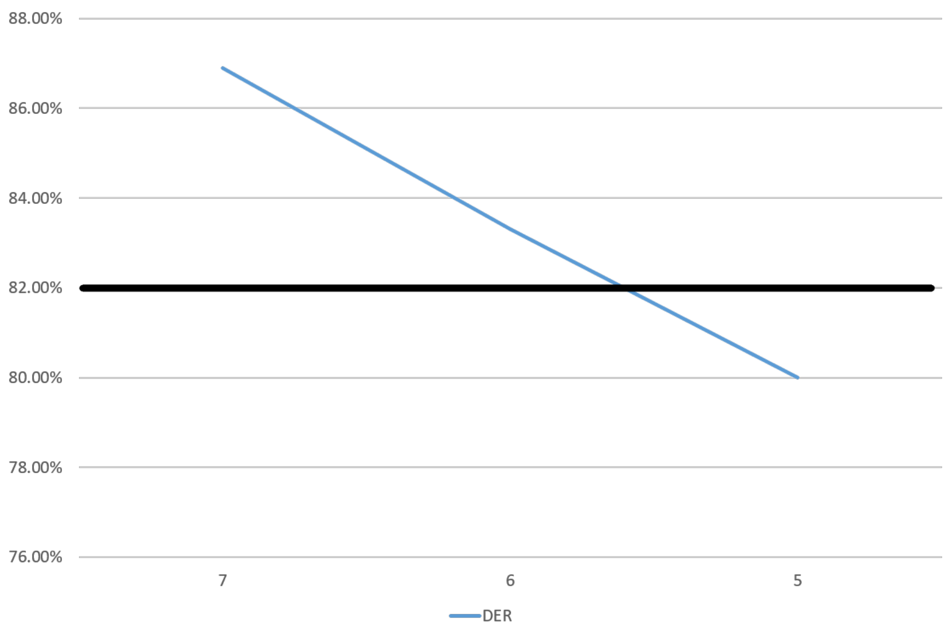

Figure 6.7: DER for varying frequency channel count

Case 4

In this case the DER is unsatisfactory, and the number of frequency channels allotted to the device is less than 3 with no competing devices sending frames to the same gateway. The number of channels in the channel mask is increased to 3, which is found to be the number of required frequency channels to attain satisfactory performance.
Unfortunately, no devices undergoing ADR were found that satisfied this case, hence no verification of this case is possible with the dataset used in this thesis.

Case 5

In this case, the DER is unsatisfactory and the number of frequency channels allotted to the device are sufficient to provide satisfactory performance. Also, since the busyness of the device is 0, there are no competing devices sending frames to the same gateway during the same time period. Hence, no modification to the channel mask should be made, and the transmission power is increased in increments of 3dB and DER is cross checked until the maximum value of transmission power is reached. This verification is not possible to perform, as the transmission power information is not conveyed in the dataset.

Case 6

In the case when the DER is unsatisfactory, and there are competing devices sending frames to the gateway at the same time, and the frequency channels used by the device are the same as the frequency channels used the least by the other devices, the only step that can be taken is the incremental increase of transmission power by 3dB and monitoring of the DER at every step. No verification can be performed in this case as well, as no information regarding transmission power is available in the dataset.

Case 7

In this case, the DER is unsatisfactory and frequency channels used by other devices sending frames to the same gateway are available to analyse and modify the channel mask to improve the performance.
The dataset was filtered to find a case with the conditions as described above. For the same device, the original algorithm is compared with the algorithm described in figure 6.6.
For the device with device address 26012244, there are 4 other devices sending frames to the same gateway. With a recorded set of 20 transmissions, the computed DER is 55.55%. With the original implementation, the DER value only increases up to 64%. During these transmissions, 26012244 uses

the frequency channels - 867.3, 867.7, 868.1, 868.3 and 868.5 MHz. The frequency channels used by the other 4 devices are 867.1, 867.3, 867.5, 867.7, 868.1, 868.3 and 868.5 MHz, with the 3 least used channels being - 867.1, 868.3, and 867.7 MHz. If these channels are used by the device in a set of 20 transmissions, a DER of exactly 80% is achieved, as modelled from the dataset.

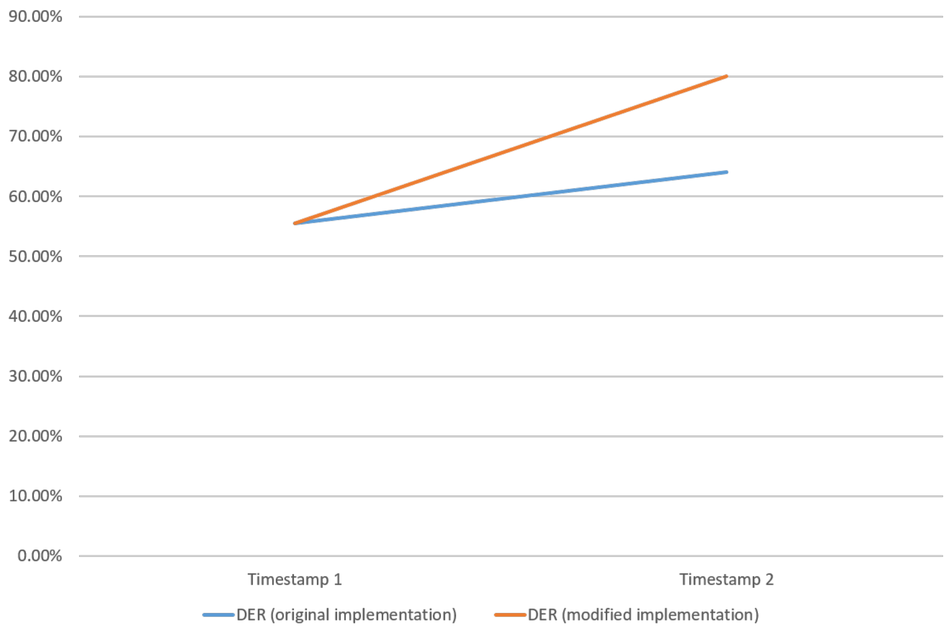

Figure 6.8: DER improvement with modified ADR model

This shows a performance improvement of 44% using the new ADR compared to 15.5% improvement using the original ADR as seen in figure 6.8.

6.2.2 Devices with Multiple Diversity Gateways

The 7 cases from table 6.2 are addressed in this section. All of these devices have a gateway diversity of more than 1.

Case 8

In this case, the DER of the device is satisfactory, and Nstep is greater than the derived NStep threshold from section 5.3.2. This means that the device can tolerate limitations being applied to its transmission parameters. As in this case, the number of frequency channels is less than 3 (which is derived as the the optimal number of frequency channels), the data proceeds to the resource constraining section of the model as seen in figure 6.5. This replicates the behaviour in the original implementation 2.3.2, hence verification

Case #	DER	Link Quality	Nature of Frequency Channels	Gateway Diversity
8	≥ 80	NStep > 4	Channel count ≤ 3	N/A
9	≥ 80	NStep > 4	Channel count > 3	N/A
10	≥ 80	NStep ≤ 4	N/A	N/A
11	< 80	N/A	Identical channel count	> 4
12	< 80	N/A	Non-identical channel count	> 4
13	< 80	N/A	Maximum channel usage	≤ 4
14	< 80	N/A	Channel usage not maximum	≤ 4

Table 6.2: Cases addressed for multi gateway diversity devices

in this case is not performed.

Case 9

Similar to the previous case, the device can tolerate limitations applied to the transmission parameters. Since the number of frequency channels used is greater than the optimal prescribed number, if the DER is more than 1.025*DER_Threshold, the number of frequency channels is to be reduced and the DER checked against the threshold after each reduction.
If the DER is less than 1.025*DER_Threshold, the data moves to the resource constraining section described in figure 6.5 which replicates the original implementation and is hence not verified.

Case 10

In this case, the NStep is less than the derived threshold, meaning that there is no scope for improving the resource usage. The performance is satisfactory and the resources are used with limit. The algorithm is ceased in this case and no further action is taken.

Case 11

When the DER is less than the defined DER_Threshold, and the gateway diversity of the device is more than 4 with the number of frequency channels being used by the device the same as the most available frequency channels, the only possible way to improve the performance is by incrementally increasing the transmission power and checking the DER after every increase. Since no information regarding transmission power of devices is provided in the dataset, this cannot be verified.

Case 12

This case is similar to the previous one, with the only difference that the frequency channels used are different from the most available channels. The channel mask is modified to use the 3 most free channels and the dataset loops back to the beginning of the model in figure 6.1.

The device with device address 26012101 displays this feature. Messages from this device are received by 6 different gateways. Measuring 20 transmissions from the device, there are 2 other devices sending frames to the same gateways during the same time. These devices use 3 different frequency channels - 867.1, 868.1, and 868.3 MHz. During the 20 transmissions, the ADR_Device uses the frequency channels - 867.1, 867.3, 868.1, 868.3, and 868.5 MHz, after which the DER is computed to be 78.9%. The following DER value on application of the original ADR implementation is 75%. If 6.6 is applied to this device, the 3 frequency channels used by the device are 867.3, 867.5 and 868.5 MHz, and the DER improves to 80.9% which is above the DER_Threshold. This value of DER is modelled from the dataset as a relation with the change in frequency.

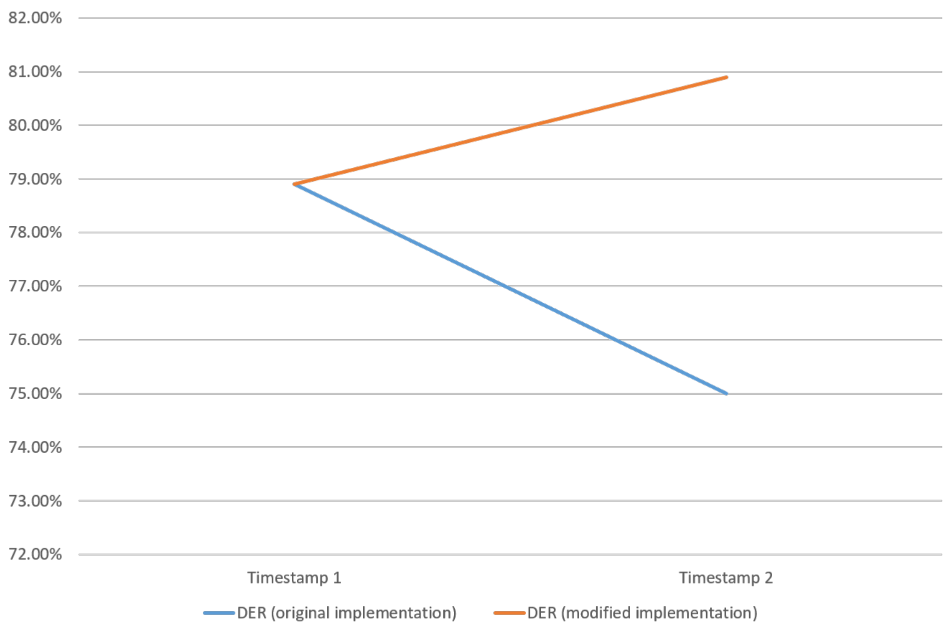

Figure 6.9: DER improvement with modified ADR model

The original implementation shows a degradation in performance by 4% whereas using the new ADR displays an improvement by 3% as seen in figure 6.9.

Case 13

When the gateway diversity of the device is less than or equal to 4, and the number of frequency channels used by the device is the same as the number of frequency channels available, no improvements to the performance via the channel mask can be made and the transmission power is incremented by 3dB stepwise and DER is monitored with every increment. Since no information regarding transmission power is available, no verification can be performed on these devices.

Case 14

In this case, with the gateway diversity less than or equal to 4, and the number of frequency channels used by the device is less than the number of frequency channels available, the channel mask is modified so that the number of channels is maximised for every device. Once the number of channels are modified, the model goes to the beginning in figure 6.1.

In the case of the device with device address 26012409, it uses 4 frequency channels during the initial 20 transmissions after which the computed DER value is 61.9%. From the dataset, the next computed DER is 63.2%. On applying the model from figure 6.6, the number of available frequency channels is computed as 8, from all the messages received by the gateways during the 20 transmissions. When the number of frequency channels is maximised, the modelled DER is found to be 95.23%, which is higher than the threshold. Using the new ADR results in performance improvement by 54% and the

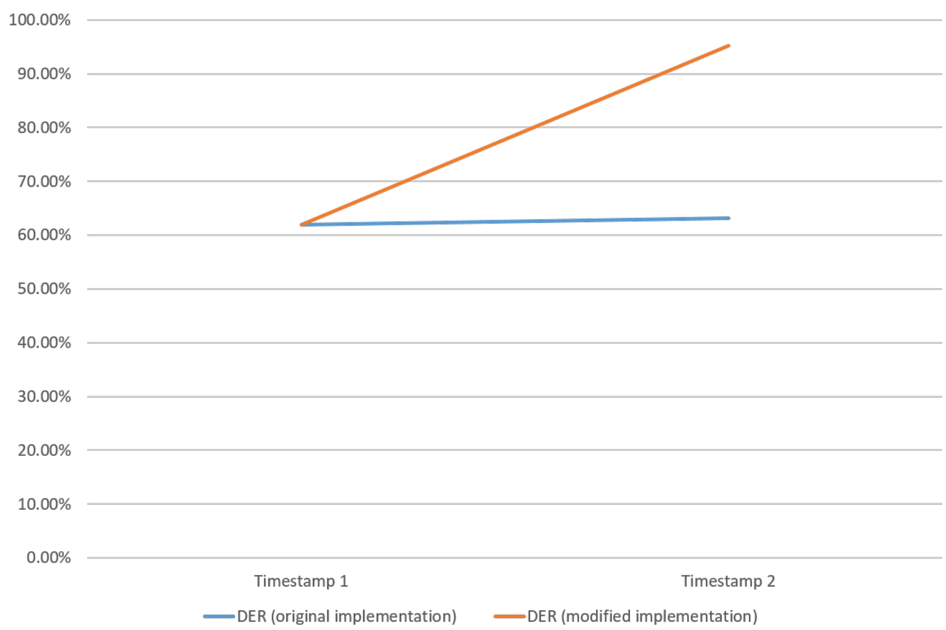

Figure 6.10: DER improvement with modified ADR model

original implementation shows an improvement by 2%.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis provides extensive analysis into the performance and behaviour of a LoRaWAN by studying and analysing data retrieved from the Network Operations Center (NOC) of the The Things Network (TTN) in the Netherlands. This data consists of meta-data of all the transmissions sent by and received on the network.

The thesis starts with the presentation of results from the traffic analysis. The dataset consists of all the uplinks and downlinks on the network over a time period of 1 month. Firstly a comparative analysis was provided between the current state of the network, and the analysis done by Blenn and Kuipers in [36]. This comparative analysis provided insights into the nature of the changes in the network over 2 years time. The analysis shows that the density of gateways has grown, where the amount of traffic received on two or more than two gateways has increased from 5% to 45%. This is also seen by analysing the signal strength variation, as higher path-loss is experienced in the later analysis, showing that frames are being received on gateways further away. This is also visualised from the more optimised usage of transmission parameters (frequency channels and data rate) in the data from 2018. This leads to the conclusion that the hardware on the newer gateways has higher sensitivity, leading to a higher data extraction rate and the development of algorithms to use transmission parameters more evenly.

Further, an in-depth analysis of the gateways was performed, focussing on the locations and a comparison with the traffic density per location. The analysis focussed on the gateways located in the Netherlands, as the traffic considered throughout this thesis is generated in this country. The effect of population density on gateway density is looked at, gateway density in different areas of the country and the usage of frequency channels as per

the population densities. This leads to the conclusion that the usage of frequency channels is uneven and is used as a factor for analysis in the next chapters to develop the ADR.
The effect of weather variation on traffic is analysed. I concluded that there is a direct relationship between the signal strength and the temperature and humidity in a short and long time-scale. In the short time-scale (24 hours), the signal is stronger with higher humidity and lower temperatures. In the long time-scale (1 month), no relation is noticed, as the variation in average temperature and humidity across the month is not sufficient to show a dependency.
The next part of the thesis consisted of analysing the data specifically to provide insights for developing the ADR model. The DER is used to measure performance as it is a measurable parameter from the dataset. The data is filtered and analysed to derive the conditions of transmission parameters to achieve the required performance in terms of DER. Based on these conditions, a model is developed to achieve these by performing a series of checks on the transmissions and make decisions about future traffic.
As it is not possible to predict the nature of the environment which affects the signal quality in turn affecting the DER, the data is used to model the results achieved on applying the developed algorithm to the different cases. In all the cases for which data is available, an improvement in the DER is achieved compared to if the original implementation was applied.

7.2 Contributions

- The first main contribution of this thesis is insights provided into the nature of the traffic being sent and received on this network, especially the comparisons made to previous measurements, other areas of improvement on the analysis of gateways and influences by external factors.

- The next main contribution of this thesis is the presentation of the process that can be followed to achieve improved performance by modifying the ADR implementation of the network.

- The final contribution is the presentation of a modified ADR which will improve the Data Extraction Rate, specifically for the nature of traffic found on The Things Network.

7.3 Future Work

On performing the analysis and work for this thesis, I came across many potential improvements to further verify this work, make it more accurate and propose other methods to improve the performance of the network. These are listed below.

- The model developed in this thesis is to be implemented on a simulation of The Things Network, which exactly replicates the nature of traffic found on the network.
- The data used in this thesis is limited to the Netherlands, extending this analysis to other areas will give an extended overview of the nature of traffic and a more comprehensive model can be developed.
- A more detailed analysis of environment impact can be performed to optimise gateway placement, such that the data extraction rate is maximised.
- The data analysis techniques used in this thesis to determine trends can be improved by implementing machine learning algorithms to predict trends that can be expected in the future. This will give a clearer indication to the modifications that will improve network performance.

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Appendix A

Literature Review : Performance of a LoRa(WAN)

This thesis analyses LoRa(WAN) to contribute to improve the performance of the network. Similar performance analysis has been carried out and reported in numerous articles and papers. This chapter presents a review of these documents and literature on LoRa(WAN) performance focussing on the scalability and capacity, and use in IoT (Internet of Things), one of the major use cases of LoRa(WAN).

A.1 Limitations of LoRaWAN

Every new technology is accompanied by limitations and restrictions; some LoRaWAN restrictions are detailed by Adelantado et al. in [12], and briefly listed below:

- The first restriction discussed is the impact of the duty cycle limitation as previously discussed in section 2.2.4 in the licence free frequency bands on network size. Using equation 2.1, and considering the maximum duty cycle as 1%, the maximum transmission time is computed to be 36s per hour per sub-band per device. Larger SF allow greater airtime, i.e. greater transmission range, but this reduces the number of packets that can be sent in the allowed time. A trade-off between communication range and number of packets transmitted is to be determined depending on the requirements of the application. The upper limit of the transmitted packet rate of a LoRaWAN device is given by $\frac{n*d}{T_{ai}}$, where n is the number of channels, d is the maximum duty cycle, and T_{ai} is the airtime with SF i.

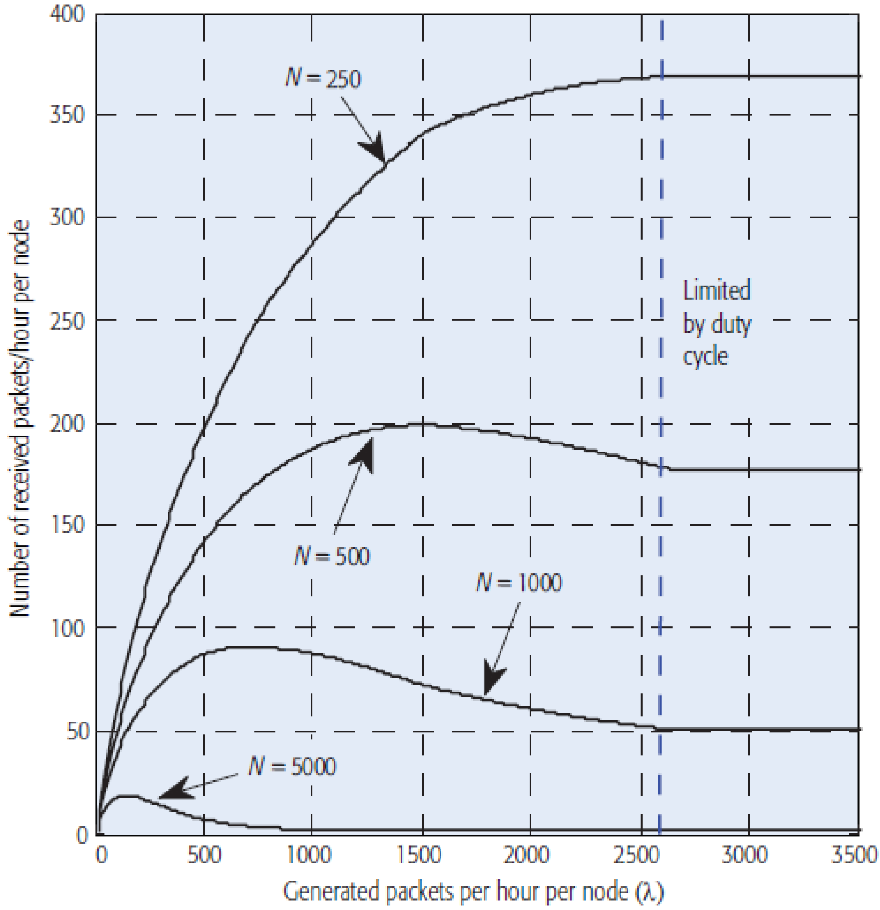

Figure A.1: Performance of the network for varying network sizes and traffic

- Another reason for performance degradation is the collision of packets. If all nodes transmit at the maximum transmission rate as described above, then the probability of collision increases. This is because the number of packets being sent simultaneously is high and the probability that 2 nodes attempt to send a packet on the same channel using the same SF is higher.

- The authors of paper [12] looked at the performance of different transmission rates for different sizes of the network shown in figure A.1. They observed that at low transmission rate, the performance is limited due to collision. If the packet rate is high, then the limitation is due to the duty cycle regulations. Further, the 'smaller' networks are limited by duty cycle more than collisions.

- Another limitation to a network is capacity drainage when acknowledgements are required for an application where reliability is a concern. For different classes of devices, different types of downlink windows are available. Following these acknowledgements, the duty cycle imposes an off period which further hampers the capacity. A trade off between reliability and number of acknowledgements has to be made to improve capacity of the network. Furthermore, since LoRaWAN uses the cellular network infrastructure, the number of end devices can be very high and maintaining the coordination of different applications on the same infrastructure can also prove to be challenging.

This paper then details some use cases of LoRaWAN to analyse the suitability of the network for each application. The first use case discussed is Real-time Monitoring. It is required in industrial automation, critical infrastructure monitoring, and actuation. These applications require low latency and bounded jitter. LoRaWAN may not be the best network due to the use of the ALOHA protocol, however small deployments could employ LoRaWAN. The LoRa Alliance has provided specific profiles for use on metering, like Wireless M-Bus. Furthermore, Smart City applications have also proven to be successfully deployed using LoRaWAN, for eg. smart parking, smart waste collection, and smart lighting systems. Transportation and logistics are seen as future areas which may be made efficient by the use of LoRaWAN.
[13] focuses on limitations due to LoRaWAN channel access, looking at the packet error ratio (PER) and packet loss ratio (PLR) to measure performance. There are 4 main issues identified in this paper.

- In LoRaWAN, when the gateway wants to transmit to the device, it raises a Pending bit in frame control, following which the device may send an uplink allowing the gateway to respond in one of the 2 receive windows (in case of class A mode). There are no details on the behaviour of the gateway when the channel is busy and it needs to transmit.

- Another issue identified is when a gateway receives 2 frames from different devices (on different channels/different SFs) requiring acknowledgement/downlinks, and if there is only 1 downlink channel for the gateway, the gateway cannot transmit simultaneously on the second receive window (due the default data rate).

- The third issue arises when the retransmitted frame collides with an acknowledgement, when duration of frame and acknowledgement is more than 1 second (delay before retransmission).

- Further on retransmissions, if all nodes reduce the data rate for every retransmission, this may increase the probability of reception however may increase collision as all nodes may end up on the lowest data rate.

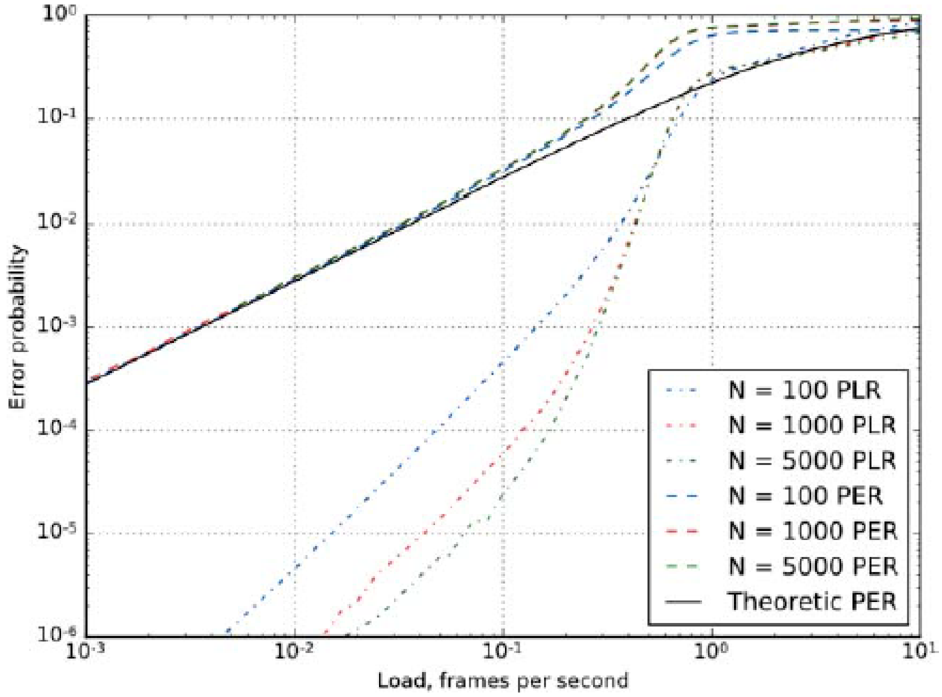

Figure A.2: Performance of the network for varying network sizes and traffic

The authors create an experimental set up to measure the the performance with PER and PLR. The set up consisted of N uniformly distributed EDs operating on 3 main channels and a single downlink channel, each channel of bandwidth 125 kHz. All 6 data rates were in use, a data rate was picked based on a pre-set probability. The Okumura-Hata path loss model was used. The end devices transmitted the most recent message and the messages were distributed according to the Poisson distribution. When the load on the network is low, for instance less than 0.1 packet/second, the PLR is negligible (0.001). This load translates into a packet generation every 20 minutes for a 100 node network or 2 packets per day for a 5000 node network. As load increases, so does the PLR and PER because a collision avalanche occurs as collision resolution in LoRaWAN is inefficient, and when the packets arrive in a non-empty queue, they get dropped. This result is similar to the result achieved in [12]. The variation in PER and PLR for different loads on the network and different network sizes is seen in figure A.2.

A.2 Simulators

Network simulators are used to develop models and propose improvements as they provide an environment to test without disrupting the real world implementation.

A.2.1 LoRaSim

In [22], a simulator, `LoRaSim`, is developed by performing practical experiments to derive communication ranges and the capture effect dependant on varying communication parameters (transmission power, frequency, spreading factor (SF), bandwidth (BW) and coding rate (CR)), and it is further used to observe the scalability of a LoRa network. The experimental set-up consists of the LoRa module from NetBlocks as the LoRa transceiver is one of the most common ones used and can represent various implementations. Communication ranges are deduced and hence the path loss model is developed using this set-up. Also receiver sensitivity is measured for different data rates, these values are used in the simulation. The collision behaviour is measured by overlapping frames and the capture effect is observed. All these features are included in the development of the simulator. In `LoRaSim`, each simulation is characterized by the set
$\mathrm{SN}_n = \{\mathrm{TP, CF, SF, BW, CR}, \lambda, \mathrm{B}\}$, where B is packet payload and λ is average packet transmission range. The derived range and collision behaviour is used to describe the communication behaviour of a simulation. There are 2 evaluation metrics defined by [22] - the Data Extraction Rate (DER) and the Network Energy Consumption (NEC). The DER is the ratio between of received messages to transmitted messages over a period of time. It is influenced by position (N), number (M) and behaviour (SN) of sinks. The NEC is the energy spent by the network to successfully extract a message. It is influenced by number of nodes, frequency and communication parameters.

A.2.2 LoRaWANSim

The effect of bi-directionality on network performance is discussed in [14] who extend `LoRaSim` to include support for the LoRaWAN MAC protocol, especially for bidirectional communication. This simulator is used to analyse the effect of bi-directionality on the uplink performance. The LoRaWANSim provides features that can simulate handshaking, network joining, exchange of security keys, adapting to optimise communication parameters etc. It implements the more complicated LoRaWAN MAC protocol instead of the features of the ALOHA protocol in the LoRaSim simulator. In [22], scaling the network resulted in low performance, however, according to [14], in addition to the scaling of the network, downlink message transmission also leads to a poor performance. The paper discusses 5 extensions made to

LoRaSim that support bi-directional traffic.

- The first is downlink and acknowledgement (ACK) data. In case of class A devices, there are 2 receive windows that open after the uplink packet is sent. These 2 receive windows allow for acknowledgements or data traffic from the gateway.
- The second is the management of the traffic in case of duty cycle restrictions.
- The third describes the collision model between the uplink and downlink traffic. They say that these will not collide due to the hardware signal processing techniques applied on the message, which permit only the intended receiver to receive the packet.
- The fourth describes the retransmission strategy, which says that it may occur if an ACK is lost due to collisions or duty cycle restrictions. Retransmission can occur up to 8 times.
- The last describes the data rate adaptation during packet loss which says that the data rate is reduced every after 2 unsuccessful transmission attempts.

A.3 General Analysis

Using the LoRaWANSim simulator, paper [14] evaluates network performance for different configurations. In the first scenario, a certain percentage of the uplink traffic counted as the downlink traffic with no acknowledgements, hence no retransmissions required. The second scenario consisted of acknowledgements for a certain percentage of uplink traffic with no other downlink traffic, the number of retries was 7. The last scenario combined the first 2. Different set-ups with different number of nodes was employed (100 - 5000). The highest data rate that could be used by an ED was used by it. Good-put is used as the parameter to evaluate performance. The first observation from the simulation is that when the size of the network increases, the downlink traffic gets exhausted. The second observation is that the good-put drops when retransmission occurs. The reduction is more evident in larger networks. The next observation says that the lack of acknowledgement may be due to the duty cycle restriction and not necessarily a lack in sensitivity of the receiver. Hence, reducing the data rate may not result in successful reception of the ACK. Also, the number of recommended retransmissions varies for the size of the network. For a network consisting of 200 nodes, 2 retransmissions are sufficient for 100% reception of ACK. Lastly, if a large percentage of EDs require AcK, the scalability is very low. For instance, if 100% of the nodes require ACK, then less than 15% capacity

is observed of the case when no ACK is required.
A QoS metrics measurement is performed in [15], to provide for developing an overlay network on top of LoRaWAN which can be used for emergency services, when communication backbones become otherwise unavailable. An overlay requires the base network to have good services which are measured by RSSI, SNR and packet delay in this paper. An overlay network can be used to send text messages, low-quality photos, GPS coordinates, alarm signals etc. Developing a mesh topology using LoRa technology is also discussed due to its robustness and ability to take different paths. A CSMA like mechanism could be integrated with LoRa to provide the mesh topology. It could also provide a reliable network that can be used for low-rate overlays. An experimental set-up is then discussed to measure the QoS metrics which include bandwidth, RSSI, SNR, packet delay and jitter. A MAC protocol was implemented which had the REQUEST, ECHO and ECHO_ANSWER stages. ED measures latency between REQUEST and ECHO, whereas the gateway measures latency between ECHO and ECHO_ANSWER. Using these values, the packet delay and jitter are calculated. A mobile ED was moved along a predefined track of 1150 m and the measurements were taken every 100 m. At 700 m, the last point for the connection was observed for the data rate used that would provide the best condition for an overlay network. Further, communication was not recorded for RSSI lower than -107 dB. The average packet delay was measured to be about 4.81 s without significant changes for distance. The QoS metrics of the network resulted in feasibility for the implementation of an overlay network.
In [17], the performance of LoRaWAN is analysed in the presence of critical noise conditions. An experimental Master-Slave configuration was set-up, consisting of a transmitter, receiver and noise generator (AWGN). Using the CCD (central composite design) technique, 36 measurements, consisting of 100 receptions of 100 packets in each measurement, were taken. This method reduces computational load and enables the estimation of a second order model for variable response. 3 sets of experimental runs are executed - centre points, axial points (extremes), and a set of points representing a factorial design.
The SF, BW, and CR are varied during the experiments. It is observed that increasing the BW causes the number of lost packets to increase. Increase in the SF improves the performance, where even a high bandwidth shows good performance (close to 0 packets lost). Increase in the CR also results in the improvement of the packet loss, however it is not as significant as what is achieved by increasing the SF or decreasing the BW. On an average, 16.38% of the packets were lost at the central point measurements with a standard deviation of 2.82%. The extreme points of CCD analysis resulted in the worst and best performance.
The authors of the paper conclude that the use of LoRa protocol results in robust communication even in the presence of high noise levels; and it can

be used in critical environments.

A.4 Performance of Communication Classes

A.4.1 Class A

A focused analysis on the performance of class-A devices is performed in [16], in the form of analytical models and then verified with protocol simulations. The performance is measured using latency, collision rate and throughput. The downlink acknowledgements are not included in the models developed in this paper, hence there will be no collisions due to retransmission. The experimental model consists of M connected EDs to a single gateways, and collisions occur when 2 or more EDs attempt transmission in the same channel, with the same SF, at the same time. The ED selects a channel, from the sub-bands allocated to it, at random at the end of any receive window, and after waiting for the off period. If no sub-band is available, the packet is queued and is sent as soon as a sub-band becomes available. A Markov model is adopted for modelling the behaviour of the ED. The collision behaviour is modelled in the case of multiple devices transmitting on the same SF, and the traffic load for a particular SF in a particular sub-band is computed. This load gives the collision probability equation, to quantify the effect of collisions in uplink only.
The model developed is used to numerically evaluate the performance of a network configuration of SF 12 and 125 kHz channels, on different usages of the sub-bands (alone and in combinations). It is observed that when sub-bands with higher duty cycles are used, lower latencies and higher capacities are achieved. A high duty cycle allows large loads to transmit at low latencies, however lower duty cycles result in lower collision rates that those bands operating at higher duty cycles. A trade-off has to be established between latencies and load.

A.4.2 Class B

A focused review of the delay in confirmed downlink frames using class B devices is performed in [11]. The delivery delay of bidirectional communication and the variation with number of channels, data rate and number of nodes, is computed using a Markov chain model. As class B devices were developed for energy efficient 2-way communication, they are studied in this paper. Periodic transmission communications from the gateway to the ED between 2 gateway beacons are allowed in this type of a device. The paper first discusses the limitations of using Class B communication - Due to the duty-cycle restrictions, every uplink of a class B device cannot be acknowledged. As class A devices are not aware of the beacon, none of the devices are forbidden to transmit during it, however in this paper, no transmission

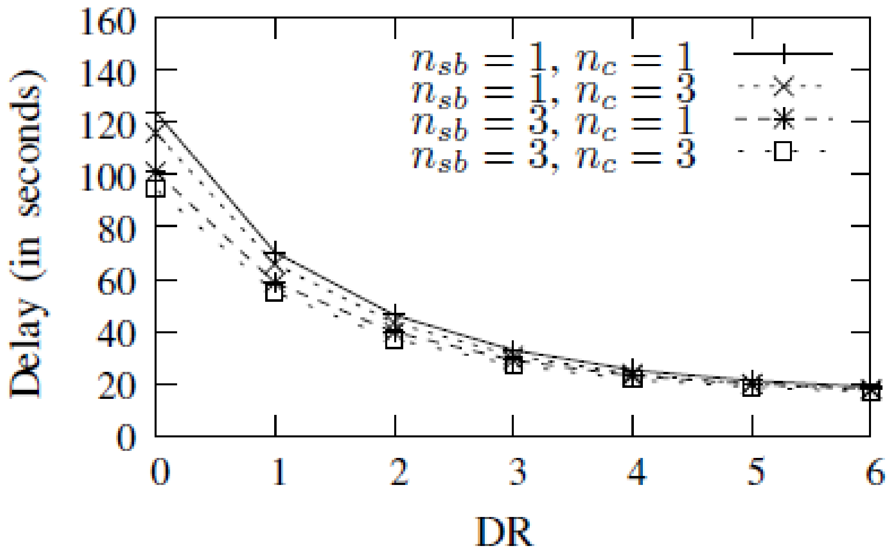

Figure A.3: Effect on expected delay due to data rate variation

during the beacon is considered. The last limitation is that the gateway may underestimate whether the sub-band is available, if a data frame is not received by it. The authors assume that the ED sends an acknowledgement (for downlink transmissions) as soon as the sub-band becomes available. The gateway keeps sending the packet till it receives the acknowledgement from the ED.
An analytic model is developed for analysis consisting of a Markov chain and probability theory. The expected delay for each state of the Markov Chain is computed depending on sub-band availability and the state matrices of the model.
The ETSI regulated sub-bands are considered for performance evaluation. A 1% duty cycle is assumed for all the sub-bands in these experiments. The expected delay as a function of data rates is plotted as seen in figure A.3, from which it is observed that as the data rate reduces, even the off-time reduces. Further, the higher the number of sub-bands, the lower is the delay; whereas increasing number of channels increases the delay. These features are also visible in figure A.3 as nsb and n_c represent the number of sub bands and number of channels respectively.

Then, the expected delay as a function of the number of competing nodes (seen as n_A in the image) is plotted. When the number of channels is low, the delay is higher with more number of competing nodes. Further, an increase in the number of sub-bands decreases the delay. This is shown in figure A.4.

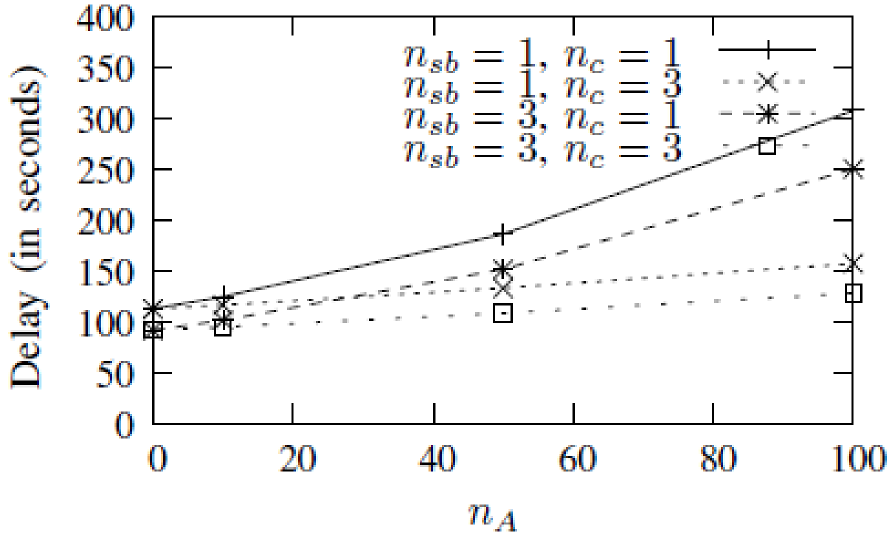

Figure A.4: Effect on expected delay due to number of competing nodes

A.5 Capacity and Scalability

The capacity and scalability analysis of LoRa(WAN) is a major area of research as it is a type of Wide Area Network (LPWAN) and long range communication is a requirement of a WAN. This analysis can provide insight about the extent to which communication is possible and how the range can be improved.

A.5.1 Practical Experiments

One of the first attempts at measuring the coverage of an LPWAN was done in [20]. The experiments involved sending packets from LoRaMotes set up in various locations (on ground and on water) in the city of Oulu, Finland, to a base station located on the University of Oulu antenna tower. The nodes used the highest available spreading factor of 12 as the maximum communication range was to be obtained, and operate on the bandwidth of 125 kHz with a transmit power of 14 dBm. The packet sent by these LoRaMotes consisted of a sequence number, the node status, and GPS coordinates to compute the location of the node. Using the size and data rate, it was computed that that each packet takes 1.365 s to be transmitted. Keeping in mind the frequency and duty cycle restrictions, only 26 packets could be sent in an hour. Using the received radio power, a radio signal heat map was generated. For the on-ground measurements, Within a 2 km range, a 12% loss of packets was observed. This increased to 15% for the range of 2-5 km. For the range of 5-10 km, a third of the packets were lost, and for the 10-15 km range, 74% of the packets were lost. For the on-water measurements, in the range of 5-15 km, 31 % of the packets were lost and in the range of 15-30 km, 38 % of the packets were lost. [20] then proposes a channel attenuation model based on the received results, and can be used for estimating communication ranges in areas similar to Oulu. The path loss was calculated by using the RSSI value. Then, the expected path loss was derived by the use of logarithmic link distance. Finally, the standard deviation of fading was derived to show the deviation between the expected and actual path loss.

A more focused analysis of LoRa network scalability was conducted by the authors of [20] in [21]. In this paper, the uplink throughput and data transmission time for a LoRaWAN ED are derived. Furthermore, they obtain the maximum number and distribution of end devices that can be served by a single base station. From the analysis conducted, it is observed that the throughput of an ED is reduced by the presence of the required down-link Rx window. The EU frequency and duty cycle regulations are yet another reason for the limitations on the performance of the LoRaWAN. The duty cycle regulations cause restriction on the transmission of burst data. Next, the capacity of the network is measured for three different configurations - three required 125 kHz LoRa modulated channels; six 125 kHz LoRa modulated channels; or six 125 kHz LoRa modulated channels, one 250 kHz LoRa channel, and one GFSK channel, with DR0-DR5 being used on all LoRa channels. The theoretical capacity in cases of optimal synchronization and ALOHA scheduling are obtained. Using a suburban channel attenuation model, capacity is then obtained for each configuration for three different scenarios - where 1 byte packet is sent every 30 s, where a 8 byte packet is sent once a day, or where a 20 byte packet is sent every 10 minutes. A general observation is that the majority of EDs that send the packets are located in a very close vicinity. Less than 10% of EDs are observed at a distance of more than 5 km. Another observation is the variation in the capacity offered by using different data rates. For example, using the DR6, 100,000 EDs can be located in 1 km-sq which send 1 packet a day. For the same scenario while using DR0, less than 300 EDs can be present. These experiments show that there is scalability potential for a single base station to serve millions of EDs, however there are restrictions regarding the location of EDs. The requirement of acknowledgements also restricts scalability. The same analysis is explained in [29].

Experimental evaluation of inter-network interference has been conducted in [28] by the authors of [20] and [21]. They evaluate the performance of simultaneous transmissions on the same channel with different data rates, and also the interference of LoRa and GFSK modulated signals, which further provides insight into the scalability potential. The experiment was set up and composed of two phases. The first phases involved sending packets from the transmitter to the receiver. The second phase involved an interferer (similar to the transmitter but with minor configuration differences) in addition to the transmitter and receiver. The results of the first phase showed that the when a higher transmission power was employed, there were more packets lost. Furthermore, for the higher data rates (DR3 DR7) the packets with payloads were getting lost in transmission. The results of the second phase showed a negative impact on performance when simultaneous data rates were used in a channel. Also, the higher data rates were more impacted than the lower data rates (where the DR of the signal was higher than the DR of the interferer). Another observation is that GFSK is negatively impacted by a LoRa signal and requires to be 9 dB stronger than the interfering signal for successful reception of majority of the packets. However, the LoRa signal is not as much affected by GFSK (a 6 dB difference shows no effect on the LoRa signal). This analysis provides important information that can be taken into account while designing an ADR algorithm to improve scalability.

A.5.2 Simulation

Using the simulator, LoRaSim, authors of [22] analysed the Scalability of LoRaWAN. They defined 2 evaluation metrics - the Data Extraction Rate (DER) and the Network Energy Consumption (NEC). The DER is the ratio between of received messages to transmitted messages over a period of time. It is influenced by position (N), number (M) and behaviour (SN) of sinks. The NEC is the energy spent by the network to successfully extract a message. It is influenced by number of nodes, frequency and communication parameters.

Three different experimental set-ups were evaluated. The first set up consisted of a single sink. Three different transmitter configurations were tested - SN^1, which had the longest airtime possible of 1712.13 ms, SN^2, which had the shortest airtime possible of 7.07 ms, and SN^3, which denoted a practical configuration as used by a deployment (The Things Network). As number of nodes increases, DER decreases. The DER of SN^1 and SN^2 has the highest difference, whereas the DER of SN^3 is close to that for SN^1. A lower DER is observed for larger packets and higher transmission rates. It is assumed that a DER > 0.9 is required for an application, 120 nodes can be supported by the SN^3 configuration.

The second set up uses dynamic parameters and the affect of these variations is observed on the DER and the NEC. The nodes are located within a radius and in the SN^4 configuration, the airtime is minimized by varying the BW, SF and CR and the TP is constant (14 dBm). In SN^5, first the airtime, then the TP is minimized. With the same DER requirement as in experiment 1, over 1600 nodes can be supported. Furthermore, reduction in airtime and TP also reduces the NEC by 89%. However the achieving such

optimal results may not be possible in real time.
The third set up utilizes multiple sinks. In this case, the previously described, SN^1 configuration is used. The nodes are set-up in a rectangular fashion such that every node can reach at least one sink. It is observed that an increase in the number of sinks results in an increase in the DER.
According to results obtained from experiment 1, the current deployments are not able to provide for more than 120 nodes which is insufficient for city applications. However, dynamically varying the communication settings by the Network Manager and/or using multiple sinks can improve scalability drastically.
In [30], the authors say that frequency and modulation adaption results in efficient management of interference and contention in long range unlicensed network (eg. LoRaWAN). Their main contribution is a a comparison between wide band (Chirp Spread Spectrum - CSS) and ultra narrow band - UNB - (BPSK) techniques. After performing simulations, it is observed that the UNB BPSK shows better range than CSS and maintains good throughput for larger range. The reason is that the CSS has a higher bit rate and a wider bandwidth. For UNB BPSK, if the received signal is 6 dB stronger than the noise power, the signal can be successfully decoded. However in the case of CSS, since the signals are spread orthogonally over the different spreading factors, multiple signals can be received simultaneously. The CSS is more robust to interference and requires the SIR to be at least -18 dB to receive the signal correctly.
To access the MAC layer, the UNB is able to send a message every 10 minutes. The CSS follows the EU regulations and the channel occupancy is 1% of the time per device. In the acknowledged mode of traffic, the spreading factor is set as a function of the number of retransmissions. The network is controlled either passively or actively in this case. With passive control, the rate adaption decisions are locally made. With active control, rate adaption requests are sent to the network manager.
The packet delivery ratio (PDR) of a UNB BPSK is very slightly better than that of the ALOHA MAC due to the capture effect where the stronger signal is successfully received. When the highest spreading factor is used for css, due to the higher bit rate and less strict channel occupancy, the throughput is higher by a factor of 3 compared to the UNB. The PDR is slightly worse compared to the ALOHA due to the requirement of acknowledgements causing an increase in the channel occupancy time and can also cause collisions. When the number of devices increase, the PDR is slightly better than that of ALOHA due to the capture effect. Another simulation of CSS is done where the SF is varying and it is observed that the PDR improves. This is due to 2 reasons - the transmissions on lower spreading factors complete faster, and the simultaneous transmissions on different spreading factors are orthogonal. The requirements of the application help decide which type of network is better suited.

The coexistence of these networks are analysed next. The first topology consists of 2 CSS networks with 2 differently located base station and each network has 60 nodes each. When a single network is considered, the performance of EDs decay as they get further from the gateway. The PER for 1000 m away is 20%. When the interfering network is introduced, the performance drops overall, and the PER for an ED 1000 m away drops to 50%. The second topology consists of a CSS network and a competing UNB network with 1000 EDs. The CSS network undergoes similar performance degradation as in the first topology with a PER of 50% at a distance of 1000 m. However the UNB performs better as it has 1000 nodes as compared to the 60 nodes in the CSS network. According to [30], the UNB performs better for less data, large number of devices, long range communication. The CSS is more suitable for low number of devices and high throughput requirements.
In addition to analysing the performance of the scalability and capacity potential of LoRa networks, application oriented analysis of capacity limits has been done in [31]. A modelling simulator has been used and a critical case measured in the center of Paris is analysed. The gateways are hexagonally distributed and follow the ALOHA protocol with a 1% duty cycle. The original ADR algorithm is modified which takes only the last 10 SNR values. There are 2 collision rules - for intra SF collisions, where the stronger signal by 6 dB will be received; and for inter SF collisions where the packet is received if power difference is higher than the SINR. The Okumura-Hata propagation model is used for urban areas and suitable modifications are used for suburban and rural areas. The shadowing effect is modelled as a log-normal distribution and the fast fading effect is modelled as a Rayleigh distribution.
The electricity meter reading use case was analysed to study the capacity. In Paris, it is estimated that there are approximately 18,000 meters per km^2. 19 gateways were set-up which covered an area of 17 km^2. The worst case positioning of a meter was in the deep indoors. 2 simulations were performed - one at 0 dBi gain and the other at -5 dBi gain. With the 0 dBi gain, the QoS over a period of 24 h resulted in 98.5% for 1500 deep indoor nodes. With the -5 dBi gain, the QoS was observed to be 95.8%. To test the capacity of the network, downlink emissions were used. A network consisting of one cell and N devices performed a simulation with and without downlink packets. These packets were introduces for every uplink and for 25% of the EDs. The more the number of downlink emissions, the worse the QoS and PER of the network. For eg., for a 2000 node network, the QoS dropped from 96.3% where there is no downlink, to 84.1% where there is a downlink for every uplink. Also, for a 1000 node network the QoS dropped from 98% to 92.25%. This shows that as the number of nodes increases, the negative impact of downlink traffic also increases. Hence downlink traffic hinders the capacity potential of a network.

A.5.3 Stochastic Model

Another method to analyse the coverage of a LoRa network is shown in [23] by developing a stochastic geometry framework to model a LoRa gateway's performance. This is also used to analyse the coverage probability of the base station, and derive the co-spreading factor interference which helps with scalability analysis. The co-spreading factor interference is a type of interference which is unique to LoRa networks. It occurs when multiple transmissions occur on the same channel with the same SF. It arises from the use of orthogonal spread sequences in the same channel to improve the capacity of the channel. Two different link outage conditions are analysed in this paper - one with regards to SNR and the other in regards to the co-spreading factor interference. The geometric model consists of the base station at the origin of a circle and EDs distributed randomly within a radius (deployment region). A single ED is focused on, and analysed how concurrent transmissions affect the transmission from that ED. The signal is not received at the gateway if the received SNR value is below the SF threshold or if the the signal is less than 6 dB stronger than any other receptions with the same SF. An observation made is that as the number of end devices increase, the coverage probability decays exponentially. This is due to co-spreading factor interference, as it may become less likely that there is a difference of 6 dB in received signal strengths as the number of transmissions increase. The co-spreading factor interference is found to be a major limitation on the scalability of a network.

A.5.4 ADR

[24] has attempted to analyse the currently used ADR (Adaptive Data Rate) algorithm and have proposed improvements, as one of the results of controlled variation of the transmission parameters is reduction in the complexity of maintenance during scaling of the network. The ED is required to set the ADR bit in an uplink message to request for data rate adaption. It then receives the MAC commands to accordingly adjust its parameters, following which, it confirms the adaption. [24] performed an experiment with the current ADR algorithm proposed by TTN [27], and they evaluated the error rate, energy consumption and scalability of the network. The algorithm operates based on the last 20 packets received, adjusting DR and transmission power whenever a threshold is exceeded. The author aims to improve scalability by a reduction in the uplink packets and downlink MAC commands. For instance, in the algorithm, the link margin is compared with a set of constant thresholds to make decisions. If the link margin is exactly in-between 2 thresholds, the decision will keep oscillating, resulting in an increase in the number of ADR requests. They solve this problem by increasing the margin to further improve the data rate. With the proposed

adaptations to the algorithm, the frequency of retransmission is observed to have decreased.
A significant observation about the fairness of the ADR model and a proposed solution is provided by Abdelfadeel et. al. in their paper [25] on a Fair ADR. They discuss the effects of the capture effect where the stronger signal dominates over the weaker one, when the difference between the 2 signal strengths is below the CIR (co-channel interference rejection) value, resulting in neither of the frames being received. They also discuss the effect of using different spreading factors, as higher data rates have a lower airtime which leads to a lower probability of collision. The solution provided by the authors is a FADR (Fair ADR) model which includes an optimised distribution of spreading factors which was earlier proposed by Reynders et. al. in their paper [26]. The spreading factor optimisation involves using lower spreading factors for devices close to the gateways. The difference in the SF distribution in paper [25] is that they implement it group-wise ordered by the signal strength, instead of over the entire network, as was done in paper [26], so that fairness in terms of distance from the gateway is taken into account while allotting spreading factors. The model further proposes a transmission power allocation method to avoid the capture effect by minimising the difference between the RSSI when the difference between the signal strength is less than the CIR value. The FADR model is measured based on fairness, DER and power usage. The model is observed to be 300% fairer than the the base model for comparison available in `LoRaSim`, however the power consumption is observed to be higher.

A.5.5 Analysis for use in Internet of Things (IoT)

IoT is a very crucial use case of LoRa(WAN) and the performance of the network in various IoT implementations has been discussed in the following articles and papers.
Authors of [10] have performed a review of using LoRaWAN for IoT applications. They start with discussing the challenges that have to be addressed by MAC protocols for IoT. To address the challenge of Bandwidth, LoRaWAN performs a trade off between communication range and message duration. Another challenge is the longevity of batteries as the number of devices is very high. To address this, the LoRaWAN controls the RF output and the output rate through the ADR (Adaptive Data Rate) algorithm for each device. IoT applications require long ranges of communication; currently 2-5 km is covered in urban areas and 45 km in rural areas. Throughput and latency are requirements that need to be addressed as well through various trade-offs.
The authors continue the review by analysing other comparable technologies which can be used for IoT. They first talk about the Bluetooth/LE technology. This provides lower data rates (max. 1Mbps) up to short distances of

100 m with low power consumption. The latest development provides higher data rates (24 Mbps) and lower power consumption. Next, the Dash7 protocol stack is discussed where communication occurs over the 433, 868 and 915 MHz bands, up to a range of 2 km. Another technology addressed is the Sigfox system which has a coverage range of 30-50 km in rural and 3-10 in urban areas. It works on the BPSK modulation.
The next topic discussed in [10] are a couple of use cases. The first use case describes renewable energy and health care solutions deployed in South Korea. They plan to set up networks for use on big data analytics on health-care, and an infrastructure for smart cars. They will deploy solutions for smart lighting, and smart traffic movement. Another use case discusses is the Cattle Traxx project which uses a LoRaWAN mesh topology. The end devices are in the form of ear tags worn by cattle which can locate the cow and relay the information to the gateway.
Then, a comparison is performed between LoRa and other similar solutions. The LoRaWAN shows many advantages over LPWAN technologies like the data rate that ranges from 300 bps to 11 Kps. Since it uses the ISM bands, communication is limited only by the regulations, and and ADR algorithm allows scaling of the network efficient usage of the channel.
Similar to [10], [18] also evaluates the use of LoRa technology for IoT. The authors of [18] also start their analysis with discussing the obstacles and challenges that have to be addressed to provide for IoT. They start by talking about connectivity between devices produced by different manufacturers, and creating a standard for manufacturing of such devices. The next obstacle addressed is of efficient energy management. As the number of devices is high, the cost of battery replacement should be low and hence batteries should last for decades. Security is then addressed by developing authentication and encryption protocols that are specific to IoT hardware. They talk about complexity and about finding ways to make the programming of such modules more efficient, especially such that the development occurs at a very fast pace. The next topic discussed by the author is use cases - such as smart power grids (where remote monitoring is required), e-Learning, smart cities, health-care and environmental protection.
The authors discuss the challenges that face the WSN (Wireless Sensor Networks) field - difficulties faced in the integration of a large number of sensors, congested RF environment leading to low efficiency and the absence of mathematical models which would allow large network simulations.
A third paper [19] that discusses the LoRa approach to provide connectivity in the IoT scenario, especially for the smart city, and analyse the efficiency, effectiveness, and architectural design. They start the analysis by reviewing current services for IoT. The standards being used are NFC (Near Field Communication) for extremely short range communication; RFID (Radio Frequency ID) for short range; Bluetooth and BLE; Proprietary systems like Z-Wave, CSRMesh, and EnOcean; those based on Wi-Fi, such as those

defined by the AllSeen Alliance. The majority of connected devices are using ZigBee or IEEE 802.15.4 based systems. They operate in the 2.4 GHz band and use the mesh topology with ranges till 100 m and operate at a high data rate (250 kbps) with low sensitivity. An improvement on the range is introduced in LPWAN devices by increasing device sensitivity from around -100 dBm for ZigBee to -150 dBm for the former. However, increasing the sensitivity causes the data rate to decrease to a range of a few hundred to a few thousand bps. This data rate is sufficient for applications that provide sporadic and intermittent transmissions like in the case of smart cities. Furthermore, connectivity is simplified as the existing cellular infrastructure is reused and single hops are used to communicate. The star-type network also provides a control of low latency required interactive applications like the control of street lights. Similar to the GPRS gateway node in GPRS services, a network server acts as the point of access and the logic controller.
The next topic discussed in the paper is an overview of 3 main LPWAN technologies - SIGFOX, Ingenu, and LoRa. The SIGFOX technology uses UNB wireless modulation, and the network protocols are kept private and no public documentation is available. Up to a million gateways can be handled by each gateway and a coverage range of 3-10 km in urban and 30-50 km in rural areas. SIGFOX only handles the network security and the payload security is the responsibility of the user. On-Ramp Wireless developed the technology called Random Phase Multiple Access, and Ingenu works on this technology. It works in the 2.4 GHz band and can operate over long-range due to a robust physical layer. The overview of LoRa is provided in 2.1.
Further, a LoRa deployment is discussed where the temperature and humidity of different rooms in a building (19 floors) is monitored. A gateway is placed on the 9th floor and 32 devices are spread throughout the building. The network underwent stress testing, by placing end devices in the elevator, and passed successfully. A coverage analysis was also performed in an urban environment. It was found that in harsh environments, the range covered by the network was 2 km in the case of the lowest date rate. A coverage range of 1.2 km was assumed in a nominal situation. They estimated that their city of approximately 100 km^2 can be covered with the use of 30 gateways.

A.6 Future Work

LoRa(WAN) is a relatively new technology with plenty of future scope in terms of improving performance.
[10] says that scaling the network to massive numbers can provide new insights and enabling roaming can improve performance. Increasing the density of gateways may help in cases where the number of EDs is large is concluded in [13] and [23] (who plan to model a multiple gateways scenario).

[17] suggests that their analysis of performance in the presence of high noise levels can be made more extensive by varying the parameters that were set constant in their experimentation. [20] plan to continue their analysis of the coverage of LoRaWAN by comparing it with coverage provided by other LPWAN radio solutions. In [22], the authors have discussed the effect of dynamic parameters and multiple gateways to improve capacity, they plan on doing a comparison of the 2 techniques to observe which provides better performance.
Reading the papers for this review and discussions with my colleague, Mr. Andri Rahmadhani, ha resulted in some potential areas of research which can provide improvements or insights into LoRa(WAN) performance. They are described as follows:

- Using a full-duplex device for the end device and/or the gateway.
- Optimizing the ADR algorithm for improving scalability.
- Extensive Uplink/Downlink interference experiments.
- Implementing a downlink scheduler which will schedule/redirect uplink transmissions that may collide with on-going downlink transmissions.
- Using the sync word in the preamble to improve capacity/scalability.

A.7 Conclusion

This chapter attempts to review the various attempts to analyse the performance of LoRa(WAN) technology. The general analysis covers the the limitation of this technology, the performance when a communication is bi-directional, the MAC layer performance while using different classes of devices, the development of the LoRaWANSim simulator, the ability to provide an overlay network, and the modelling of the system using analytical and Markov chain models. The analysis for use in IoT discusses how LoRaWAN performs when it is employed for IoT applications and a comparison of LoRaWAN with other LPWAN technologies for the same. The scalability and capacity analysis discusses various models and the development of the LoRaSim simulator, scalability in different network configurations and situations, suggestions on improvement of the ADR algorithm, analysis of the effect of inter-network interference, and the performance when 2 different types of networks coexist.
As described in A.6, there is a wide range of possibilities of further evaluation of the performance, which may result in suggestions to improve the performance of a LoRa(WAN).