Improving the Gateway Placement Algorithm in Long Range Wide Area Network (LoRaWAN)

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Presented by:
Petros Smangaliso Mnguni

Supervisor:
Dr Pragasen Mudali
Dept. of Computer Science
University of Zululand

Co-Supervisor:
Prof Adnan Abu-Mahfouz
Council for Scientific and Industrial Research

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Dedication

In memory of my great grandparents (Ngwenya, Mntimande, Bambolunye, Mabuya).

"Thank you for believing in me, isiphinde yabanjwa".

Declaration

1. I understand that plagiarism is a violation. Plagiarism is about using the work of someone and claiming it as your own.
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Smangaliso Mnguni
December 2, 2022

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May God bless you all.

Abstract

Internet of Things (IoT) is expected to grow exponentially such that the number of devices connected to the internet will be up to 125 billion by the year 2030. IoT end node devices rely on Gateways for data transmission to the internet and to ensure coverage for IoT devices, Gateways need to be optimally placed. However, physical infrastructure and topography as features of the target area are essential for IoT Gateways optimal placement. Recently, Wireless Mesh Networks (WMN) has gained an important role in current communication technologies. It has been used in several applications such as surveillance and rescue systems. Furthermore, the network congestion can be minimised and throughput can be improved by placing many Gateways in the network but on the other hand, deployment cost and interference will increase. Therefore, this work focuses on the Gateway placement algorithms on the newly developed wireless technology called Long Range Wide Area Networks (LoRaWAN) protocol and its performance.

A review of existing Gateway Placement Algorithms has been conducted to bring together the state-of-the-art WMN, Mobile Ad hoc Networks (MANETs)-Satellite, Backbone Wireless Mesh Network (BWMN), Vehicular Ad hoc Network (VANET), 5G cellular network, and Low Power Wide Area Network (LPWAN).These Algorithms were studied in different networks to distinguish each of their strengths and weaknesses that require improvements. Literature provided insight into the performance of the existing Gateway placement algorithms in both short-range and long-range transmission. However, it is still not clear how the algorithms perform in a network that supports long-range transmission technologies such as LPWAN. Arising from the foregoing is the need to evaluate the performance of short-range algorithms in LPWAN environment; to improve the algorithms for a long-range technology such as LoRa; assuming that they showed the prospect of overcoming the drawbacks mentioned in the literature review.

This study has improved existing Gateway placement algorithm by firstly evaluating the existing algorithms that were implemented in a different environment i.e., short-range transmission, and determining the strength and drawback of those algorithms. Secondly, after the identification of an algorithm with some promising features that can be integrated into a long-range transmission, it is then improved for Gateway placement in LoRa technology. The algorithm implemented previously was for a different purpose and was implemented in a different network. However, due to its capability in the previous environment which can be beneficiary in a newly developed LoRa technology, the algorithm was improved and implemented in LPWAN environment to improve

Gateway placement.

The simulation results showed that the improved algorithm outperformed the existing algorithms. Some of the outstanding observation with the improved algorithm the SF7 accommodated an average of 25% for LoRa nodes created in both network scenarios where other algorithms could accommodate only 20% of the network average. The increase of Gateways in the network can help to reduce the energy consumption by LoRa nodes even though it can be expensive.

Research Outputs

The following publications were developed during the registered period of research study:

1. Mnguni, Smangaliso, Adnan M. Abu-Mahfouz, Pragasen Mudali, and Matthew O. Adigun. " A Review of Gateway Placement Algorithmson Internet of Things", Accepted for 2019 International Conference on Advances in Big Data, Computing and Data Communication Systems (icABCD), South Africa, Drakensberg Sun Resort, Winterton, KwaZulu Natal, pp. 1-6. IEEE, 2019.
2. Mnguni, Smangaliso, Pragasen Mudali, Nombuso Sibeko, and Matthew O. Adigun. "LoRa Gateway Placement at the University of Zululand: A Case Study.", Accepted for 2019 International Conference on Smart Applications, Communications and Networking (SmartNets), Egypt, Sharm El Sheikh pp. 1-6. IEEE, 2019.
3. Mnguni, Smangaliso, Pragasen Mudali, Adnan M. Abu-Mahfouz, and Matthew O. Adigun. "Performance evaluation of Spreading Factors in LoRa Networks. "Accepted for 2021 In Towards new e-Infrastructure and e-Services for Developing Countries: 12th EAI International Conference, AFRICOMM 2020, Ebène City, Mauritius, December 2-4, 2020, Proceedings 12, pp. 203-215. Springer International Publishing, 2021.
4. Mnguni, Smangaliso, Pragasen Mudali, Adnan M. Abu-Mahfouz, and Matthew O. Adigun. "Impact of the Packet Delivery Ratio (PDR) and Network Throughput in Gateway placement LoRaWAN Networks." Southern Africa Telecommunication Networks and Applications Conference (SATNAC) 2021 (Accepted and published)

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List of Acronyms

ADR	Adaptive Data Rate
ACK	Acknowledgements
AP	Access Point
BW	Bandwidth
BWMN	Backbone Wireless Mesh Network
CSIR	Council for Scientific and Industrial Research
CDs	Co-ordinate Devices
CSS	Chirp Spread Spectrum
CR	Code Rate
CF	Carrier Frequency
CBGPA	Clustering Based Gateway Placement Algorithm
DR	Data Rate
SF	Spreading Factor
IoT	Internet of Things
IGWs	IoT Gateways
IGs	Internet Gateways
SSGWs	Solution Specific Gateways
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LTE	Long Term Evolution
V2I	Vehicle-to-Infrastructure
QoS	Quality of Service
WMN	Wireless Mesh Network
ILP	Integer Linear Programming
RSSI	Received Signal Strength Indicator
OP	Optional Points
SN	Sensor Networks
PDR	Packet Delivery Ratio
PER	Packet Error Rate
SINR	Signal-to-Interference-plus-Noise Ration
FADR	Fair Adaptive Data Rate
FEC	Forward Error Correction
FLoRa	Framework for LoRa
PHY	Physical Layer
TP	Transmission Power

UDP	User Datagram
ED	End Device
NS	Network Server
IDE	Integrated Development Environment
NED	Network Description
WSN	Wireless Sensor Networks
LoS	Line of Sight
UZ	University of Zululand
ToA	Time on Air

Chapter 1

Introduction

1.1 Chapter overview

The Internet of Things (IoT) is intended to connect devices to the internet transforming them to smart devices and improving the quality of life of human beings. These devices (such as Smart phones, Laptops, washing machines, Sensors, etc.) need to communicate with each other and be mutually identifiable to be called smart objects. IoT devices connected to the internet are growing exponentially and the number is expected to reach 125 billion by the year 2030 (Marais et al., 2017) and (Zorbas et al., 2020). These smart devices communication can be deployed using short-range technologies such as Bluetooth, infrared, and ZigBee, or long-range technologies such as Sigfox, NB-fi, and LoRa. In addition, IoT devices have the capability of being located inside buildings, underwater or underground to improve sectors such as health system, agriculture, transportation, manufacturing, and logistics to save costs while operating at a higher efficiency level(Lauridsen et al., 2017) and (Mnguni, Abu-Mahfouz, Mudali and Adigun, 2019).

Low Power Wide Area(LPWAN) usually provides a long–range transmission, wireless connectivity (using a star topology), and increased power efficiency (Magrin, 2016). LoRaWAN is one of the technologies provided by LPWAN which has many capabilities and some promising features. Many of LoRa devices use LoRaWAN standards for communication and can improve power efficiency as their estimated battery life is 10 years(Xiong et al., 2015).

IoT Gateways are used to facilitate communication between the Internet and smart devices (Karthikeya et al., 2016). Therefore, Gateway placement is essential to maximise connectivity for every device present in the network, and reduce latency and overall deployment cost. IoT gateways become even more significant for protocol conversion and data handling purposes because they are responsible for data transmission.

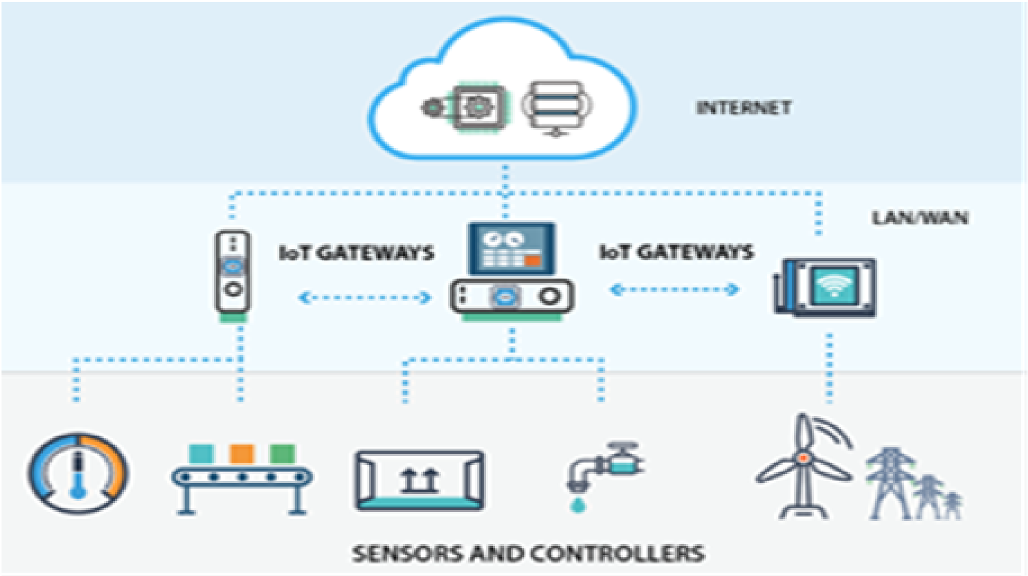

Figure 1.1: IoT sensors and controllers connected to the IoT Gateways Glória et al. (2017).

These IoT gateways shown in Figure 1.1 are used to facilitate communication between sensors and controllers to the internet. They can also provide simple administration where basic operation or functions can be conducted while maintaining security.

The internet and mobile communication networks play a major role in data transmission among people. Although Wireless Sensor Networks (WSN) are used in smart devices for short distance communication however, with the lack of uniform standardisation in communication protocols for both networks, it is not easy to connect mobile communication networks with WSN or the internet. This drawback results in non transmission of data over a long distance due to limitations in WSN's transmission protocols (Zhu et al., 2010) and (Ali et al., 2019). Therefore, the IoT Gateway is introduced as a new network equipment type with the development of the IoT to make communication in the network easier and close the gap between sensor networks and traditional communication networks.

Gateway placement is essential in long-range transmission of data for the commercialisation of the IoT technology due to its capability to facilitate data transmission in a long-range since the demand for a large amount of data transmission, low-power and long-range (LoRa) arises. For a long-range, low power communication, the LoRa technology is available but not suitable for transmission of large amount of data due to low transmission rate. The LoRa communication technology is a low power, long-range wireless protocol developed by Semtech. High extendibility, low power consumption and high efficiency as compared to 3G/4G technologies are the main advantages of the LoRa technology. However, low transmission rates are the notable disadvantage of the technology (Kim et al., 2016) and Ndiaye et al. (2017).

Gateway placement algorithms have been proposed and implemented in different networks for both short-range and long-range transmission technologies. In many cases, it is proven that long-range transmission technologies in LPWAN such as LoRa, Sigfox, and NB-fi technologies are impacted by obstacles like waves, hills, trees, and high buildings (Li et al., 2017) and (Anzum et al., 2021). These factors result in a high packet loss rate, Gateway failures, and communication link failures which are common problems for Gateway placement in every network.

Researchers have been exploring different algorithms for different purposes such as a selection of minimum Gateways to be deployed in a smart city scenario (Magrin et al., 2017), an election of Gateway to connect to the source vehicle to monitor the traffic using Long Term Evolution(LTE) and network cost reduction without compromising the Quality of Service (QoS)(El Mouna Zhioua et al., 2014). This was used to ensure that no matter the number of Gateways placed in the network in comparison to the total number of devices, the transmission remains flawless. However, all these algorithms were implemented in the different environment as that of LoRa technology and they were not meant for the LoRa Gateway placement in a LPWAN environment.

Normally, the mentioned algorithms experience drawbacks such as poor performance due to excessive amount of energy usage per transmission and utilization of energy when packets collide (Harwahyu et al., 2018). Other shortcomings of these algorithms involve the unequal distribution between LoRa nodes, scalability, Packet Delivery Ratio (PDR), and robustness to dynamic channel conditions especially when the network starts to expand (Hauser and Hégr, 2017). Issues such as allocation of Spreading Factor (SF) to increase the capacity of the network and attain optimum data rate by aiming at the Gateway and LoRa nodes that decrease the convergence time are still major problems in these algorithms(Finnegan et al., 2020).

The algorithms referenced in the above paragraph show good characteristics in solving some of the above-mentioned factors that caused the drawbacks mentioned in the Gateway placement algorithms that have already been implemented in LPWAN for the long-range transmission technologies. Therefore, the need to improve one algorithm based on capabilities to address the Gateway placement in LoRa transmission arose.

1.2 Problem Statement

In solving the Gateway placement problem in IoT networks, a set of different algorithms exist for different IoT networks. Algorithms that supports short-range technologies have demonstrated the ability to address LPWAN Gateway placement problem such as link of communication failures and Gateway failures by using k-coverage-connectivity (Zhou et al., 2004) and (Jia et al., 2005).This has been observed due to the fact that some of the short comings between these two transmission ranges are common.

There are existing long-range algorithms which still need to be improved due to the drawbacks mentioned above. Some of the algorithms were only tested in the networks that support short-range transmission technologies such as Wi-Fi, RFID, Bluetooth, and ZigBee. However, it is still not clear how the algorithms perform in a network that supports long-range transmission technologies such as LPWAN. Arising from the foregoing, is the need to evaluate the performance of short-range technologies algorithms in LPWAN environment to improve the algorithms for a long-range technology such as LoRa assuming that they show the prospect of overcoming the drawbacks mentioned.

1.3 Rational of the study

The application scenarios may be the same for different technologies e.g. Sigfox technology act as both the network service provider and the technology. On the other hand, LoRa technology focuses on providing the technical solutions and developing the technology. Therefore, some of the benefit for solving the LoRa Gateway placement in LPWAN are for infrastructure monitoring scenarios (including different consumption metering cases such as electricity or water consumption and monitoring of gas) and communication from vehicle to infrastructure. (Petäjäjärvi et al., 2016).

LoRa as LPWAN technology contain some attractive features for day-by-day application domain. Remote wellness monitoring and smart health are part of those domains to provide real-life cases which might be at the receiving end of this study. It considers how patients can use remote monitoring at their homes and at hospitals through a single system or how employers can monitor wellbeing at work or even soccer players during matches. A well-positioned Gateway in LoRa networks will enable doctors or employers to deploy a single base station to cover the whole facility (e.g., a shopping mall, a parking area, a university campus, a factory or a hospital) (Petajajarvi et al., 2015).

LPWANs high power efficiency guarantees the end user terminal(e.g., Sensors) a long life even if powered by batteries. In that aspect, a smart home scenario is a prime example of benefits from the LoRa gateway placement since smart home is embedded with sensors, automation equipment, network communication and information for home appliances to make sure that the communication is flawless among these sensors (Reddy et al., 2019).

1.4 Research Questions

This research aims to address the following research questions:

- How can IoT Gateway placement algorithms for long-range transmission technologies enhance data rate in LPWAN?
- How do we maximise network coverage with the use of SFs and Data Rate in LPWAN Gateway placement?
- Which position is the best for locating Gateways for a long-range technology like LPWAN when using LoRaWAN?

1.5 Research Goal

- The goal of the study is to improve Gateway placement for Low Power Wide Area Network.

1.6 Research Objectives

The goal of the study has been broken down into the following achievable objectives:

- To establish the state-of-art Gateway placement and identify existing algorithms for computing the candidate locations for Gateways to be placed and have the optimal location selected from them
- To compute the maximum coverage of the network through Adaptive Data Rate (ADR) and SFs in LPWAN.
- To determine the best possible position in which Gateways can be placed for a long-range technology in LPWAN when using the LoRaWAN algorithm.
- To design and implement the new algorithm in LoRa networks.
- To test the newly implemented algorithm in LPWAN environment using LoRa technology.

1.7 Research Approach

The first step taken in this research was a thorough review of existing Gateway placement algorithms in both short and long-range networks. The algorithms were classified by the type of networks they belonged to and by identifying their capabilities from the environment in which they are implemented. This helped to evaluate the advantages and disadvantages of each algorithm and identify where improvements can be made. The intention is to identify algorithms drawbacks and improve them for the LPWAN environment.

After the review the next step was the feasibility study to ascertain how feasible our study was and determine the type of hardware machines and software versions to use. The third step involved configuring the simulation tool identified as the one suitable to be used with the computer machines which had a sufficient power to run those experiments. The University of Zululand (UNIZULU) was responsible for the hardware element and some of the installed LoRaWAN software versions which were not open source.

In the fourth step, after the hardware machines were tested and necessary software were installed to ensure that the entire environment was functional. The network scenarios were then created, and multiple evaluations were conducted in the network to examine the aspect of the implemented algorithm with evaluation metrices such as network size, PDR, SF impact and network throughput. Lastly, the insight of LPWANs regarding their capabilities such as low power consumption and long-range transmission were documented after thorough analysis.

1.8 Dissertation Organization

The rest of the dissertation is organised as follows: Chapter 2 gives a detailed background study. Chapter 3 is a review of literature on existing Gateway placement algorithms implemented in different networks including WMN, BWM, MANET-Satellite, 5G Cellular-Network, VANET, and LPWAN for both short and long-range transmission. It also includes several aspects of LPWAN exploration and the evaluation of this newly developed and promising technology. Chapter 4 provides the details of the developed Improved Gateway placement algorithm. Chapter 5 presents the details of the simulation setup used. Chapter 6 contains the results obtained from all simulation experiments conducted as well as the discussion for each result. Chapter 7 presents the discussion of the research questions and objectives based on the results obtained from experiments conducted. Lastly, chapter 8 concludes the dissertation by giving the summary of the research, answers to the research questions, and suggestions for future work.

Chapter 2

Background

2.1 Chapter Overview

This chapter provides the background of LoRa and LoRaWAN technology.

2.2 Context

The IoT is the merging of the physical and cyber worlds. It is intended to bring all objects into the internet and turn them to smart devices. IoT end node devices rely on Gateways to connect them to the internet for data transmission. With the rapidly growth estimation of the number of devices connected to the internet, Gateways need to be optimally placed to ensure coverage for the end node devices. The main reason for the exponential growth of devices connected to the internet is that there are many application areas where IoT can be applied.

Since the number of devices connected to the internet grows exponentially, LPWAN in IoT has became essential for long-range coverage,low power consumption and low cost effectiveness. The communication of these devices can be deployed through short-range technologies such as bluetooth,infrared and Zigbee, or long-range technologies such as SigFox,NB-Fi, and LoRa (Citoni et al., 2019). Figure 2.1 shows different IoT application scenarios.

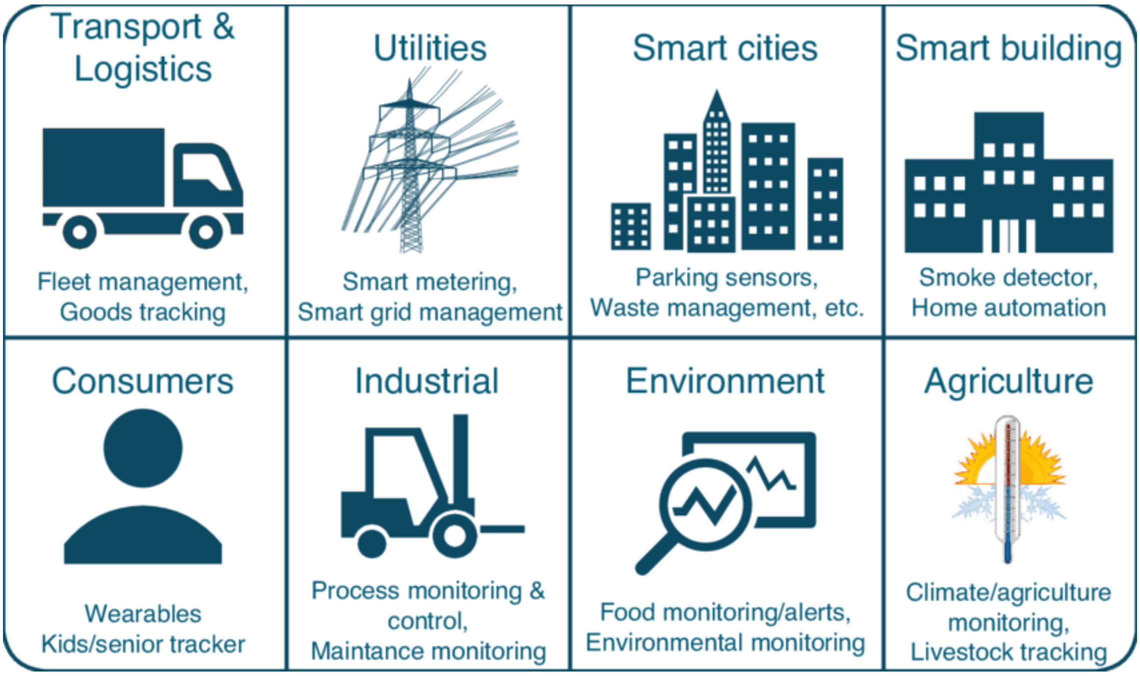

Figure 2.1: Different IoT application scenarios. (Boulogeorgos et al., 2016)

2.3 IoT Gateways

This section illustrates IoT Gateway using a smart home which is a typical IoT application to give further clarity. As stated in the previous section, intelligent building, SmartMeter, logistics among others are all covered in the application of the IoT. In modern smart homes, in order to provide convenient living environment that is green, safe and comfortable, the automation equipment, network communication, home appliances and sensors are all embedded to ensure proper communication. However, IoT Gateways play a significant role in the process in terms of interconnecting multiple smart devices to form an in-home network and share resources and information among various home appliances.

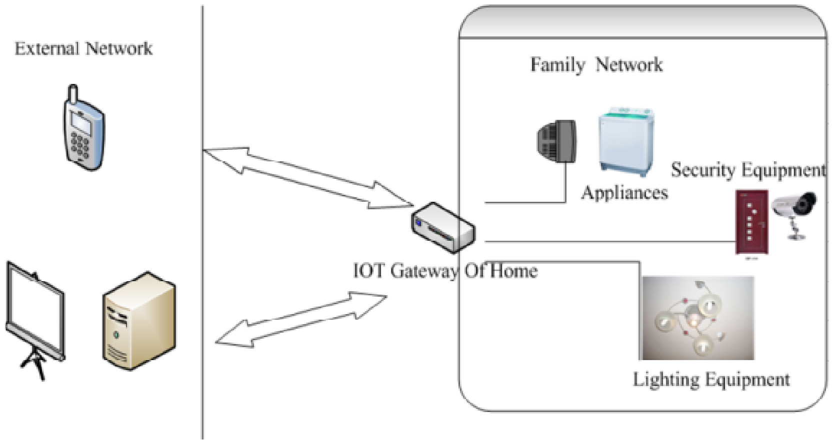

Figure 2.2: Smart home scenario used. (Zhu et al., 2010)

Gateway placement is essential for a flawless communication since IoT Gateway plays a very important role in connecting the in-home network to the external network. As shown in Figure 2.2, the scenario provides the access interface to the external network. The in-home IoT Gateway can support the interconnection amongst the equipment with different network protocol and also integrates different IoT networks protocols. Therefore, the smart home equipment can be controlled by the user through the IoT Gateways.

2.4 The LoRaWAN Protocol

Companies using the IoT devices are already benefiting from the use of LoRaWAN. LoRa network relies on the two components of LoRa and LoRaWAN in a protocol stack in which each of these components correspond with different layers. The LoRa Alliance however describe LoRaWAN as an open standard where Semtech developed the LoRa physical layer which remains the sole LoRa integrated circuit. Figure 2.3 represents protocol stack of IoT devices, Gateways and network server, while Gateways acting as a middleman forwarding messages between sensors (i.e. IoT devices) and the network server, sensors and network server consist of an application layer.

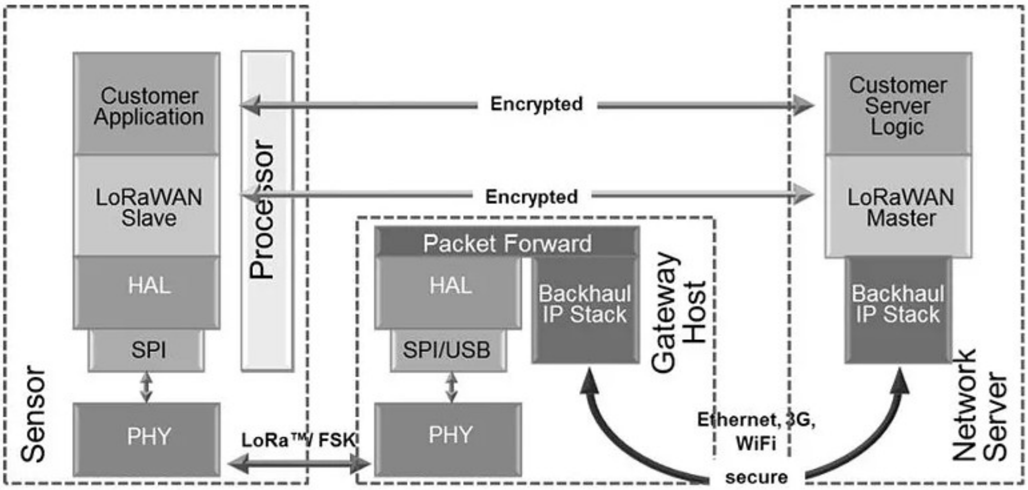

Figure 2.3: Protocol stack in LoRaWAN with various devices (Schroder Filho et al., 2016).

2.4.1 LoRa

LoRa is a new promising and fast-growing network designed for unlicensed,low power and long-range operation. In order to meet the data and range requirements, LoRa wireless uses a chip- ad-spectrum (CSS) modulation with options for different bandwidth (BW) and SF for modulation optimization. 433 MHZ, 868 MHz and 915 MHz are all ISM bands where LoRa operates depending on the jurisdiction of the band divided up into channels(Wixted et al., 2016). In LoRa networks, the combination of BW and SF compromise speed for range. SF and BW are not only the parameters that affect the communication range and data rate but also center frequency, code rate (CR) and transmission power (TP). The ratio between the chirp rate and data symbol rate is labelled as SF. Therefore, tuning the reachable distance and the data rate is allowed through the configuration of SF. In fact, higher SF allows longer range at the expense of low data rate, and vice versa. The configuration of TP is mostly dependent on the BW and region used for transmission, whereas the CR is regarded as forward error correction which affects the data transmission airtime. The center frequency relies on the ISM band of chosen region. Finally, the BW plays a significant role in the data rate of transmission. 14dBm is the limited TP in Europe with the duty circle of 1 percent for air time. However, the usage of these bands differs across the world (Bor et al., 2016).

2.4.2 LoRaWAN

LoRaWAN is the system architecture and ALOHA based communication protocol for a network using LoRa physical layer. It can communicate over the air with a Gateway(s) and it also involves protocol stack with LoRa wireless, usually network servers communicate with the Gateways and LoRa physical layer to create communication between LoRa nodes and the Gateway. To reduce the complexity of LoRa nodes in the network, LoRaWAN depends on ALOHA based MAC protocol(Andrew, 1996). LoRaWAN technology has the capability of adapting its principal parameters to optimize the energy consumption. Figure 2.4 shows the architecture of the LoRaWAN network. LoRa/LoRaWAN, RF interface is used to facilitate communication between end nodes and the Gateway. Ethernet,3G/4G, Wi-Fi, etc. are all non-LoRaWAN networks which are used by the Gateway to transmit frames to the network server and TCP/IP SSL is responsible for the protection of critical application from the threat of attack (Petrić et al., 2016).

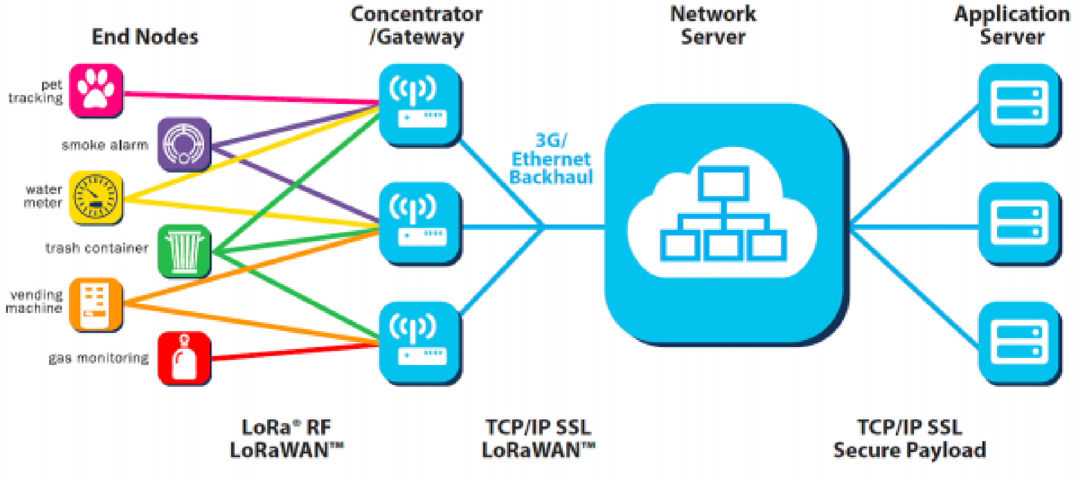

Figure 2.4: The LoRaWAN architecture (Hammi et al., 2017).

Class devices (A,B or C) are all defined by LoRaWAN standard for different scenarios to be catered for. Class A is the most power efficient class among the three since the devices are unreachable most of the time. This class should be implemented by all LoRa vendors due to its ability to provide the longest battery life. The transmission to the Gateway is sent by a device after class A. Two short downlink receive windows are open during transmission which may allow the device to receive the data directly from the Gateway.

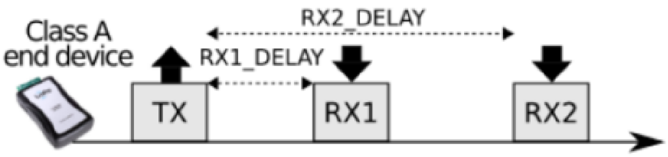

Figure 2.5: LoRaWAN class A end device receive time slot (Van den Abeele et al., 2017).

Figure 2.5 demonstrates that any downlink communication outside of these windows will be sent after the device's next transmission. Class B adds periodic receive windows that emerge as a modification of Class A, whereas a receive window is kept open all the times by Class C. Class A is the most difficult to communicate with since the transceivers are in sleep mode until a packet is sent. However, they are still the most energy efficient devices (Van den Abeele et al., 2017). As LoRaWAN follows the ALOHA scheme, devices have the advantage of transmitting packet at any time. However, they need to ensure that the duty cycle limits are adhered to.

2.5 Chapter Summary

This Chapter provided insight into the main theme of this dissertation. We started with the context of IoT and IoT applications explaining the IoT applications scenarios and IoT Gateways significant role in the IoT sector. The LoRaWAN protocol was further explained in details and how LoRa and LoRaWAN components benefit from the LoRaWAN protocol is explained in the protocol stack with various devices such as sensors, Gateways and network servers.

Next, we defined LoRa and LoRaWAN and how everything is modulated in a LoRaWAN architecture based on communication protocol. Lastly, we defined LoRaWAN standards which are class devices (A, B or C) and how they help cater for different scenarios. The next chapter presents related work from literature.

Chapter 3

Literature Review

3.1 Chapter Overview

This chapter provides a review of relevant literature. The findings from this study provided the insight into the problem formulated and proffered possible solutions. The literature review is divided into two subsections. The first is on the short-range transmission based Gateway placement algorithms and the long-range transmission-based Gateway algorithm in wide area networks. The second section includes the drawbacks of several studies which help identify the need of this study.

3.2 Gateway Placement Algorithms

To date there are a number of Gateway placement algorithms proposed and implemented in different networks for both short-range and long-range transmission technologies. These algorithms have demonstrated the ability to address various problems in the networks. However, there are still limitations in terms of positioning the Gateway to enable better network performance especially in the LoRa networks.

3.2.1 Short-range transmission gateway placement

This sub-section presents different algorithms which support short-range transmission in different networks. The algorithms address different problems in the network such as (Karthikeya et al., 2016) who proposed a Selection Algorithm using the smart city as a scenario. This algorithm called NewIoTGateway-Select determines the minimum Gateways to be used in a particular network. This algorithm evaluates the position of a Gateway and how many Gateways are to be deployed in that particular area or given scenario. For a Gateway placement, candidate locations are computed by NewIoTGateway-Select algorithm and optimal locations are often selected from them. IoT Gateways (IGWs) and placement of Solution Specific Gateways (SSGWs) use computational geometry to calculate the possible candidate locations using Selection algorithm from the chosen locations of the candidate. The algorithm selects the optimal locations for IGWs and SSGWs and handle the failures of links in the network and Gateway failures by including k- connectivity and k-coverage algorithms respectively (Matni et al., 2020).

The disadvantage of this algorithm is that in order to provide the full coverage for a given number of Coordinate Devices (CDs), the sum of the number of IGWs and SSGWs must be equal to the total number of required Gateways. For instance, if there are 600 CDs in a network, a total of 141 total Gateways needed (33 IGWs + 108 SSGWs) according to NewIoTGateway-Select algorithm which may result in the unreasonable cost for full coverage. Nonetheless, NewIoTGateway-select can be optimized to develop efficient routing algorithms for IoT networks of three dimensions (3D) which are also optimized to address issues of Gateway placement. Therefore, the improved Gateway placement algorithm aims to optimise the existing algorithm for Gateway placement in Low Power Area Network.

Selecting the right Gateway for every action is important. This was explored by (El Mouna Zhioua et al., 2014) who proposed the Co-operative Traffic Algorithm that selects a Gateway to connect the source vehicle to the Long Term Evolution (LTE) advanced infrastructure under the scope of vehicle-to-infrastructure (V2I) communications. This algorithm is a Quality of Service (QoS) and multi-criteria based scheme optimization. The appropriate Gateway decision is made by performing the fuzzy logic. The approximation theory of dealing with a complex system uncertainty can be viewed as a fuzzy logic. The fuzzy logic has two objectives. The first objective is to develop a computational model that requires human intelligence for problem-solving task and the model can also perform its reasoning. The second objective is to evaluate the importance of trade-off between cost and precision in the algorithm LTE infrastructure that must be connected to source vehicle performed by a decentralized scheme. In order to transmit to the infrastructure, a Gateway selection based on the traffic class is basically a Quality of Service (QoS) balancing scheme.

Li et al. (2008) proposed an algorithm for Gateway placement optimal solution in a Wireless Mesh Network (WMN). They assumed graph G, consisting of MR nodes, is connected. This algorithm is divided into two parts: Mesh Router attachment and Gateway selection. Gateway selection was the first approach to be presented in the first part, which was intended to find a minimum dominating set with maximum weight. The second part which considered load balancing among Gateways. A Gateway is selected as the primary Gateway and one or more gateways can be attached in every MR.

Hamdi et al. (2012) explored an algorithm called KCMBC algorithm. This algorithm consists of three important steps. The first step is the use of expiration time and the degree of computing node metric. The main purpose of the node metric is to figure out how long IoT nodes device can maintain their possible connection with their current neighbours and still be clusterheads eligible. The second step is based on using the protocols FloodMin and FloodMax for clusterhead election. The final step is node leaving and joining the cluster in which the node is used in cluster structure to update cluster and maintain it.

In the process of electing clusterhead which is the step two, the metric value of each and every node is broadcast to the k-hop neighbours, and the candidate clusterhead election proceeds according to the reception of other metric nodes. To ascertain which node serves as clusterhead various mechanisms are used to bring concurrence among nodes. However, the drawback of this algorithm is that: it is very important to consider partitioning measurements characteristics. With this kind of algorithm, an enhancement would be training it such that it can also add new mechanism or modify KCMBC since coping with partitioning was not the only purpose but was also designed for other specifications in the network.

Ahmed and Hashim (2015) studied a novel approach using Genetic Algorithm with the purpose of solving Gateway placement problem and find the best solution in terms of hopes number and Internet Gateways (IGs) number where transmission of packets take place between Mesh Router (MR) and IG. The Genetic Algorithm approach for gateway placement problems has different types of sections such as network encoding for real-world representation of a network and network decoding. The initial population of a given number of IGs and MR are generated randomly, and Selection Operation (OP) picks the individual number from a certain current species using probability and the crossover. Nonetheless, the algorithm can be optimized by considering different parameters in testing such as population size, tournament size, and crossover type.

Maolin et al. (2009) presented a Backbone Wireless Mess Networks (BWMNs) novel algorithm to address the problem of the placement of Gateways. The location of Gateway problem is solved by using the incremental clustering algorithm, such as iteratively assigning mesh routers to already identified Gateways and incrementally identifying Gateways. At least one Gateway in the algorithm is identified in each iteration. In the identified Gateway, the algorithm assigned at least one mesh router and the number of mesh routers that has not been assigned to any Gateway decreases by one. Thus, after most $n - 1$ iteration the incremental clustering algorithm terminates and, the total number of mesh routers is denoted by n.

In addition, the assignment of mesh router is accepted if the constraints are not violated. When the algorithm terminates, it is guaranteed that a feasible solution will be generated. The algorithm iterates many times and this delays the process making it worse. However, only one Gateway is identified by the algorithm in each of the iterations and the algorithm assigns only one MR to the Gateway. Optimizing the process of iteration in this algorithm can be virtual so that at least it identifies more than one Gateway and assign more than one mesh router to the Gateway.

Benyamina et al. (2009) proposed a Clustering Based Gateway Placement Algorithm (CBGPA) with perfect handling scalability of network CBGP Algorithm which guarantees end-to-end bounded delay communications. Once the whole graph is connected and the set of Access Points (APs) is defined, CBGPA implements the cluster construction procedure between the APs at halfway position start by placing a Mesh Gateway (MG). For every unvisited MG by AP, among all AP neighbours, the closest one will be selected by the peer AP. An immediate neighbour (within one hop distance) is not a candidate. When all mesh nodes marked the algorithm stops, it is always iterative. In some cases, the routing path is selected as MG when there is one AP left. All present nodes belong to disjointed clusters when the algorithm process terminates, and each node is headed by one MG. The total number of formed clusters represents the minimal number of MGs that guarantee the required delay with a minimum deployment cost. However, the drawback of this algorithm is that the same set of experiment is needed to run more than once in order to evaluate the effectiveness of CBGPA.

Kiess and Khan (2014) proposed a Centralized algorithm against Distributed algorithm for Gateway placement functionality in 5G cellular networks. The Centralized algorithms are used for positioning the Gateways in the middle of the position and the configuration is used as a baseline. In the Centralized algorithm when the number of Gateways is proposed, a Centralized algorithm works perfectly against Distributed algorithm for Gateway placement functionality in 5 G cellular networks. When the number of Gateways increases, n biggest cities strategies are used to assess the influence on the network. The gravity model is used to calculate the traffic between two cities. The main disadvantage of this algorithm is that even if the Gateways are centralized, it is not guaranteed that all nodes around it will connect perfectly.

Gravalos et al. (2016) studied an Integer Linear Programming (ILP) to reduce the network cost with respect to the total number of devices that are deployed. The main aim of this algorithm is to priorities the QoS. QoS refers to any kind of technology that controls data traffic to minimize delays, latency and packet loss on the network. Furthermore, in the ILP algorithm at the facility location different none-gateway communication devices are deployed. These devices differ in the total cost and capabilities of transmission. To ensure adequate capacity for the flow demands that need to be addressed, each device in the network is selected with respect to each specification of the transmission. Nonetheless, the cost of Gateway placement using this algorithm is still expected to grow as technology improves daily. This is the main disadvantage of ILP..

3.2.2 Long-range transmission gateway placement

Choi et al. (2018) proposed Fingerprint-Algorithm- Based Positioning. In most IoT applications, positioning is an essential element. The aim of the proposed algorithm is to track the moving object in a specific area by implementing LPWA IoT services, where LoRa networks can be developed. This study consists of an offline and online phase. A fingerprint algorithm is used in a LoRa-based Gateway positioning process in the offline phase. The characteristics of signals are collected for each sample point from all service area and stored in a database. In the online positioning phase, the location of an end device is estimated through the database search. In this algorithm, all uplink packets have an end device ID, timestamp and a sequence number. The firmware of IoT Gateways and LoRa end-devices should be modified to send an uplink packet and to process them for positioning. End-devices send uplink packets to Gateways for positioning following which Received Signal Strength Indicator (RSSI) information is accessed at the Gateways. Nonetheless, power consumption is still a disadvantage in this algorithm due to the online phase. However, multiple Gateways can be implemented using this algorithm.

Tian et al. (2018) explored two greedy algorithms which are Weight bipartite and PGL algorithms for optimization of the Gateways locations. In this approach, the authors were concerned about placing Gateways so that jointly the maximum number of IoT sensors are served, and all possible pairs of sensors are superimposed for the decoding crescents. In the Weight bipartite graph algorithm, two sets of vertices are defined. All possible Optional Points (OPs) contain in the first set, where pairs of decoding crescents an intersection of boundaries point defines the OP. All possible ordered pairs of Sensor Networks (SNs) are composed in the second set of vertices. The main drawback of these algorithms is that as the number of SNs increases, it is likely that the WBG algorithm will become more time consuming because the number of SNs OPs will grow rapidly.

Fargas and Petersen (2017) proposed a multi-lateration algorithm for the estimation of the device location purposes, and from each Gateway the packet received time. When the transmitter is not synchronized with the receiver, multi-lateration algorithm is introduced in that system as a geological technique. The receivers do not need to be synchronized to each other as transmitters need to be. Thus, the intersection of at least two hyperbolas is the location in this technique. Only the Gateways were synchronized with each other. The IoT tracking system does not have synchronization with the end device. Therefore, by the time packets were received by each Gateway, the information was available. There are several Gateways supporting LoRa technology on the market. The chosen one was Kerlink because a GPS receiver is embedded in the Gateway. Therefore, all Gateways are synchronized by using the timestamp from the GPS satellites.

Loh et al. (2022) proposed a novel graph-based gateway placement approach. The main focus was collision probability reduction, which directly increases reliability in LoRaWAN deployments. Their approach performs similar to state-of-the-art related work in the worst case and reduces the required number of gateways by up to 40% while reducing the collision probability by up to 70%.

3.3 Tools considered for LoRa Performance

Performance plays a vital role when dealing with LPWAN technologies. LPWAN has the advantage of low cost deployment without compromising the network coverage and throughput. Furthermore, every IoT commercial company attempting to deploy IoT device will prioritize a single technology with the capabilities of handling both indoor and outdoor connectivity needs. Other use cases of LPWAN such as equipment monitoring, asset tracking and healthy monitoring devices are essential and need 24/7 connectivity (Neumann et al., 2016). Therefore, these items performance metrics such as signal strength,battery life expectancy, throughput and packet delivery are considered highly important.

Simulation, emulation and conduction of experiments are all forms of performance evaluation. Simulators are very convenient, extendible and highly configurable and they avoid the delay of building testbed. However, the drawback can provide overly promising results. Emulator enables the visualization of software and hardware in one computer system and it usually acts as a bridge between experiments and simulators, but it cannot properly record the radio frequency environment of a deployed testbed (Dludla et al., 2013; Neumann et al., 2016). Testbeds configurations are not as easy as simulation configurations because building them is time consuming and costly yet they remain a popular and accurate method for evaluating wireless networks.

PDR and its inverse Packet Error Rate(PER) remain the most influential performance matric. The computation of packet loss requires a lot of attention to ensure that sufficient data points are used.

3.4 Performance of Spreading Factors in LoRa Networks

In a LoRa network, LoRa nodes transmit their packets in a broadcast manner, while Gateways listen for transmissions on all available channels and all possible SFs (Ousat and Ghaderi, 2019). Therefore, in Low Power Wide Area Networks, LoRaWAN based protocol using permanent outdoor testbeds take into considerations matrices such as link checks, payload length and PDR when evaluating Adaptive Data Rate (ADR) performance. ADR schemes assign primarily either the slowest data rate (SF12:BW25) or the fastest (SF7:BW250) regardless of the distance (Marais et al., 2019). SFs play a significant role in the transmission of packets between IoT devices and Gateway(s). For example, LoRa devices can be configured to use different TP, CR, BW settings, and SFs resulting in over 6720 possible settings which make it difficult to determine setting that minimises transmission energy cost while meeting required communication performance. (Bor and Roedig, 2017).

In LoRa technology the number of chirps per symbol used are defined by SFs. SF configuration ranges from the element of SF:6 to SF:12. In terms of data transmission, it is observed that the higher the SF, the higher the receiver sensitivity which compromise time taken to transmit packets from the end nodes to Gateway(s) but which enables long-range communication. In the radio communication frequency network, separation is possible by employing different SFs since SF are orthogonal to one another(Zorbas et al., 2018). Success probability can be used to express density covered by Gateway with a given frequency, provided nodes are distributed uniformly over a certain radius d centered at the Gateway. Nodes with multiple SFs are considered considering both inter-SF and intra-SF.

The collision is caused by transmission using the same frequency or SF. Intra-SF collision occurs between two LoRa frame with the same frequency and SF which makes LoRa frame with highest power to be decoded. Tts power in the Gateway exceeds minus 6dB. A collision of inter-SF occurs between two LoRa frames with different SF and same frequency. However, in this scenario if the received power of the first minus the received power of the second is higher than the Signal-to-Interference-plus-Noise Ration (SINR) the first frame is demodulated as shown in Table 3.1.

Mostly it is assumed that the modulation uses fixed BW, which results in symbols that last twice the duration when SF is increased by 1. The rate at which chirps are transmitted is increased by the bigger BW and repeatedly bitrate of modulation. If the noise or interference messages have high robustness due to an increase in transmission time for chirp and chirp symbol errors are more luckily to occur.

Table 3.1: Minimum SINR required to demodulate per SF. Varsier and Schwoerer (2017)

SF	**Min SINR (dB)**
7	-7
8	-9
9	-11.5
10	-14
11	16.5
12	-19

3.5 Performance of the Adaptive Data Rate (ADR) Scheme

In a LoRa Gateway placement ADR is essential for the easy network scalability when more Gateways are added to the network. It also increases the network capacity since the transmitted data packet using different SFs are orthogonal and can be transmitted concurrently (Kufakunesu et al., 2020). Therefore, the ADR scheme is defined and designed to set the TP and data rate of static nodes, it also specifies the ability of the Gateway to use LinkADReq messages to specify new transmission settings to devices. Maximising the life expectancy of the battery and increasing the overall capacity of the network are amongst the main goals of ADR. The scheme has the ability to adjust the list of allowed channels, repetition rate (number of time to repeat a frame), TP and devices DR. This can be achieved by estimating a link budget(Slabicki et al., 2018). ADR can also run asynchronously at the network server and at a LoRa node. Network server consists of most configuration complexity in ADR to ensure nodes simplicity. LoRa alliance specifies the algorithm. This algorithm modifies the TP and decreases SF.

A suggested approach to ensure scalability is estimating congestion by examining the network's throughput, RSSI and the number of connections at a gateway before nodes are sent LinkADRReq messages (Kim et al., 2017). When determining the power transmission and SF assignment RSSI are used by Fair Adaptive Data Rate (FADR) in its calculations. Furthermore, after creating a group of 50 nodes by ordering the nodes based on RSSI, FADR assigns SFs to them. In (Sanchez-Iborra et al., 2018) another approach which increases the ADR algorithm's complexity by suggesting adjusting the averaging of SNR history and data rate before incrementing TP is revealed. Finally, the approach proposed in (Kim and Yoo, 2018) which targeted the addition of the number of devices using low SFs for maximising network coverage. This approach tracks the number of nodes per SF.

In Cuomo et al. (2017) two algorithms were explored by the researchers with the aim of focusing on the network performance as a whole instead of individual nodes performance. These algorithms has the capability of maximising data extraction rate and network throughput more similar to PDR. The first algorithm named EXPLoRa-KM dealt with overcrowded areas with their SF allocation targets and the second one, EXPLoRa-TS balanced the traffic load between available SF channels.

ADR enabled trade-off between energy consumption, robustness, and network throughput through the support of LoRa while the BW is fixed. In Figure 3.1. ALOHA is used by the LoRa devices for a random transmission in the UL and satisfy an additional maximum p0 =1 % duty cycling police. According to this cycling policy LoRa nodes with higher SFs transmit less often when compared to those with lower SFs, for a simplicity BW=125KHz is kept constant for every transmission. However, packet loss may still occur if concurrently received signal of the same SF and frequency interfere at the same gateway regardless of simplification. Finally, $l1$, $l2$...,ln denotes Euclidean range between gateway and LoRa nodes (Georgiou and Raza, 2017).

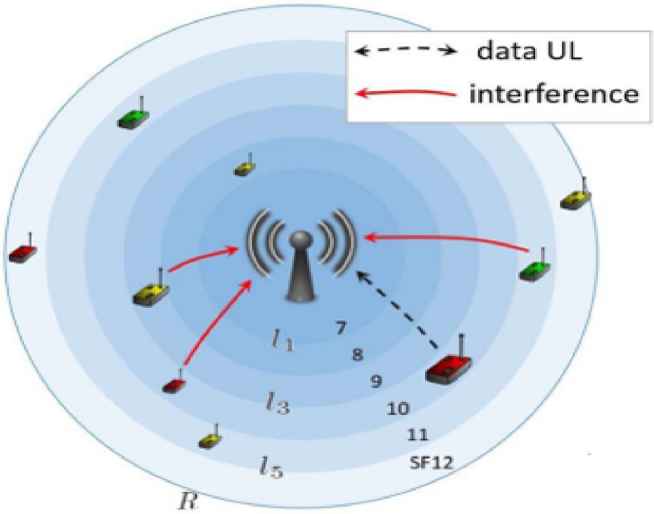

Figure 3.1: System setup in the uplink consisting of just one gateway, and several concurrently transmitting end-devices located uniformly in a radius of R km.

3.6 Limitations of Long-Range Gateway Placement algorithm.

The analysis performed shows that there are several different algorithms in Gateway placement with each having its approach, advantages, and disadvantages. However, some of the algorithms seem to be similar but have differences in the type of network, transmission range, strength, limitations and network size covered. For example, all the studies considered in this paper implemented algorithms for the same purpose of Gateway placement, but they were implemented in differing networks such as WMN, LPWAN, MANET, and VANET. The expected transmission range of Gateways was found to differ greatly across the various network types, resulting in differing network deployment areas (Mnguni, Abu-Mahfouz, Mudali and Adigun, 2019) and (Wu et al., 2009). Also shown in Table 3.2 are the general limitations faced by different algorithms such as scalability issues, complexity, and cost.

Some of the limitation that are addressed in the long-range include high power consumption since these devices transmit in a long distance and implementing many Gateways in the network can be costly as well. Therefore, a device that consume less energy can last long such that packets reach the destination without complications. Time taken is also a factor that needs to be considered when working with LoRa technology. When the network expands most LoRa technology takes a lot of time to transmit which makes the network a bit slow. However, most algorithms that show capabilities of solving the short comings for Long-Range transmission were implemented in a short-range transmission hence the improvement to implement in the LoRa technology.

Table 3.2: Literature Gaps Summary (Mnguni, Abu-Mahfouz, Mudali and Adigun, 2019)

Literature	Transmission Range	Network Model	Objectives	Strength	Limitations	Networks Size	Av.Node Speed
Li et al. (2008)	30m	WMN	Optimizing number of GW average MR-GR	Better Load Balance	Uses Brute-Force search each choice it involves validation	200m x 200m	-
(Hamdi et al., 2012)	70 m – 100 m	MANET-Satellite	Bridging partitioned networks	Minimize economical cost and optimize network cost	Scalability issues	100m x 100m	4.4m/s
Ahmed and Hashim (2015)	-	WMN	Minimize variation of MR-IG-hop count	Robustness and Scalabilit	Only uses the sequence of 1s and 0s (Binary)	-	-
Tian et al. (2018)	-	LPWAN	To address Gateway interference	High PDR	Low average contention computational complex	20 x 20 m	-
Maolin et al. (2009)	-	BWMN	To find Gateway placement	Provide Quality of Service (QoS) and feasible gateway placement	Limited gateways to be deployed	10 x 10 m	30 runs
El Mouna Zhioua et al. (2014)	250 m	VANET	To cover most of the area. Consider QoS traffic class constraint. To make a decision on appropriate gateway placemen	Better performance in terms of packet loss by using kcoverageconnectivit	Very complex to implement	-	0.3mb/s
Karthikeya et al. (2016)	10,30,50,60,100 m	IoT Networking	To minimize deployment cost. The enhance network coverage	Take care of gateway failures and link failures	A lot of complex calculation	1km x 1km	-
Benyamina et al. (2009)	-	WMN	To optimize the model of cost deployment. To optimize the model of average congestion	Guarantee an upper bound length for every potential path between any Mesh node and its nearby MG	-	-	9 runs
Kiess and Khan (2014)	40 km	5G Cellular Network	-	If at least a certain fraction of traffic is transmitted over long distances the cost does not explod	cost	360.000km	-
Gravalos et al. (2016)	LTE-A	IoT network	To provide QoS Constraints	QoS	Expensive installations	1000m x 1000 m	-
Choi et al. (2018)	Long Range	LPWAN	To evaluate the accuracy and usability of the fingerprint algorithm.	Can implement multiples of gateway	Creation of interpolated maps in the offline phase.	340m x 340m	-
Fargas and Petersen (2017)	5km-15km	LPWAN	To design and implement a LoRaWAN tracking system	Transmits signals in a long rang	Unlimited resources	2km – 3km	-

3.7 Chapter Summary

This section presented a review of relevant literature. It detailed the findings of a review of literature on the LoRa Gateway placement algorithm in LPWAN. The chapter started by giving the objectives and the context of why Gateway placement is needed for IoT network domain and provide some scenarios where it is applicable.

The LoRa Gateway placement is an ongoing development which support a long-range communication under the LPWAN. It uses the LoRaWAN communication protocol provided by LoRa Alliance which consists of physical layer. LoRaWAN communication protocol is unique because it is an open source which makes it more familiar to researchers, unlike other protocols provided by LPWAN. Forward Error Correction (FEC) and Chirp Spread Spectrum are used by LoRa as a combination to reduce noise interference for long-range communication. Star-of-stars topology is one of the common topologies used in LoRaWAN networks. LoRaWAN transmission settings such as power transmission and data rate of individual node are controlled by ADR schemes which is one of the most important features available in order to optimize network throughput.

Once the Gateway placement algorithms has been developed specifically as mathematical models. There are various ways of evaluating their performance. These include testbeds, experiments either in the laboratory or field deployment and simulations. Latency, network throughput, PDR, PER, DER and energy consumption are all amongst the matrices used in the literature review for different algorithms included. Table 3.2 shows some of the algorithm performance evaluation and comparison.

Chapter 4

Improved LoRa Gateway Placement Algorithm in LPWAN

4.1 Chapter Overview

The difficulties experienced by the LoRa networks in terms of Gateway placement were discussed in the previous chapters. The feasibility of two building blocks for an improved LoRa Gateway placement algorithm in Low Power Wide Area Network (LPWAN) was discussed in Chapter 3 through a review of literature. First is the feasibility of implementing the short-range algorithms into LPWAN to solve Gateway placement problem in a long-range transmission as the newly developed technology. Secondly, is the feasibility of integrating an already implemented algorithm in long-range transmission with some of the promising features to solve Gateway placement issues from the short-range algorithms.

This chapter builds upon the two foundational building blocks provided above to develop a suitable algorithm for LoRa Gateway placement in LPWAN. The other algorithms implemented in long-range for different purposes and scenarios are also considered in the development of new Gateway placement algorithm since they give insight into the complexity and issues the LoRa technology might experience. This is determined through evaluation and theoretical analysis. These complexities include:

(i) Join Gateway Placement and resource allocation (Liu et al., 2019) and (Gravalos et al., 2016).

(ii) Fault-tolerant LoRa network design (Gupta et al., 2016).

(iii) LoRa Gateway placement algorithm Quality of Service (QoS) in LoRa networks design (Reynders et al., 2017).

(iv) Identifying key parameters of LoRa in designing the placement algorithm (Liando et al., 2019).

This chapter presents the design and implementation of an improved Gateway placement algorithm for LoRa technology in LPWAN, that takes above mentioned complexities into consideration. improved algorithm is intended for use as the major algorithm to determine the best possible place where a Gateway can be placed. Through the use of Gap statistics method (Tibshirani et al., 2001) which is used to determine the number of LoRa Gateways present or optimal number of clusters in the network, improved Gateway placement algorithm has the advantage of improving the receiving packets by knowing the correct number of Gateways and overlapping the radius of the antenna.

4.2 Design criteria

This section provides the details of the first step taken to assemble the design criteria for this algorithm. An algorithm is developed from a core set of design criteria for the proposed scheme. Some of these design criteria were described in (Zhou et al., 2019). Figure 4.1 illustrate a three-tier hierarchical LoRa network architecture which is proposed for the improved algorithm design criteria including the components described such as:

- *Maintaining network connectivity between LoRa node and Gateway.* The infrastructure LPWAN usage scenarios described in (Raza et al., 2017) suggest that the connectivity between LoRa node and Gateway should remain available since these two components are the backbone of entire LoRa network. The uplink radio packets are forwarded by LoRa Gateway to LoRa network server after adding metadata such as Received-Signal-Strength-Indicator (RSSI) and Signal-Noise-Ratio(SNR). Conversely, on the downlink, LoRa Gateway performs transmission requests coming from LoRa network server.

- *Maintaining the transmission of packets (sent/received).* LoRa network server is responsible for processing packets and protocol analysis after receiving them from the LoRa Gateway. Forwarding application layer data to application server, scheduling acknowledgment, performing network management mechanisms, filtering duplicate uplink packets and checking legality of LoRa end-device are all functions that need to be implemented in the LoRa network server.

- *Design criteria feature for LoRa Gateway placement.* Power consumption, low complex algorithm, network throughput and data rate.

- *Application server in IoT cloud.* The processing of application layer payloads, encryption and decryption is done by the application server.

- *Distributed communication system.* LoRaWAN design planning of communication methodology requires similarity to that used for cellular systems, based on the need to estimate the environment, device, and the coverage radius in a cell.

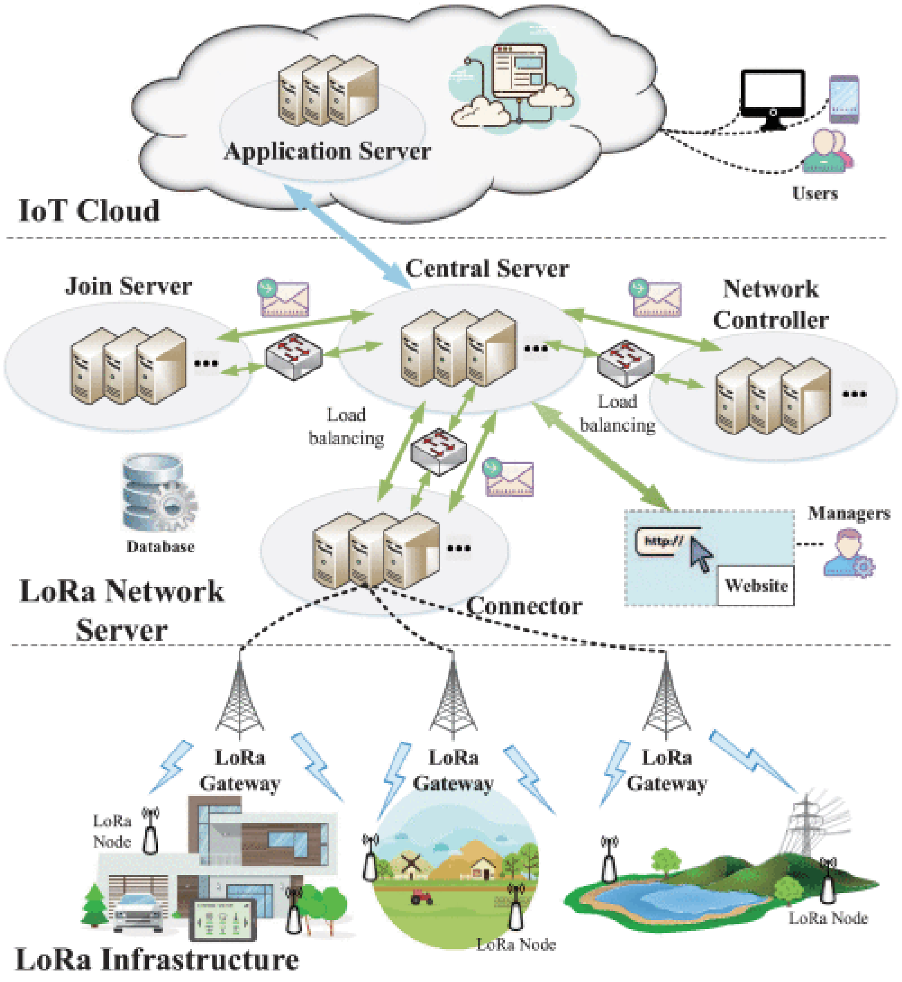

Figure 4.1: Illustration of three-tier LoRa network architecture (Zhou et al., 2019).

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4.3 Improved LoRa Gateway Algorithm

Improved LoRa Gateway algorithm is intended to be low power consumption, and low-complex algorithm for Gateway placement in LoRa transmission. The algorithm has the goal of improving the ability to place a Gateway in a suitable location to maximise the network throughput and improve the data rate. This algorithm works under the assumption of two (2) LoRa devices: a set of IoT devices and Gateways where on the one hand, IoT devices are randomly distributed in the network and on the other hand, Gateways can be placed at a given location based on a placement algorithm.

Improved LoRa Gateway algorithm adopts the improvement of existing Gateway algorithms to achieve the goal of a reliable and accurate method to correctly place the Gateway and improve network connectivity. The employment of the existing Gateway placement algorithm features discussed in Chapter 3 has previously shown a phenomenal ability of finding optimal location for the Gateway(s) and improve the quality of transmission in a long-range.

The improved Gateway placement algorithm is listed in Algorithm 1. The Gateway placement algorithm is designed to find a suitable location for LoRa Gateway(s) to maximise the network connectivity while maintaining communication between LoRa nodes and the Gateways. Furthermore, according to the Gateway placement literature in Chapter 3, this algorithm will result in the possibility of achieving the positioning of higher packets delivery ratio.

Algorithm 1 Execution logic of improved Gateway Placement Algorithm.

```
Input: R = Simulation radius
Input: GWs= number of LoRa Gateway simulation.
Input: EDs= number of LoRa devices in a simulation.
Input: M= potential Gateway location.
Output: Installed Gateways = , SF Assignments, power allocations.
While there are empty locations do
  for $i \leftarrow$ empty location indices do
    Add i to list of installed Gateways.
    Assign SFs and powers and calculate the
    objective as $F_{new}$.
    if $F_{new} \geq F_{old}$ then
      $next \leftarrow j$
      $F_{old} \leftarrow F_{new}$
    Remove i from the list of installed Gateways.
    end if
  Add next to the list of installed Gateways.
$F_{old} = R$
```

In summary, the improvement of Gateway placement algorithm is advantageous for the following reasons:

- It is expected to help LoRa Gateway cover many square kilometers in the given environment.
- It is a simple and effective algorithm which supports two-way multichannel communication as it is essential for LoRa Gateway based on LoRa technology.
- The algorithm is robust and high processing performance is guarantee of scalability.
- The algorithm is reliable and there no additional network hardware.
- It improves the network throughput and maintains the availability of all LoRa devices present in the network.

Improved Gateway placement employs a lot of features from other existing algorithms to make it more reliable and easier to maintain. Some of these features are defined in Matni et al. (2019), (Araujo et al., 2018) and (Rady et al., 2019).

The Gateway positioning results in knowing where to place Gateways ascertain which Gateway the LoRa node should be associated with to balance network load and maximise received signal strength (Matni et al., 2019). The authors derived the following theorem:

Theorem 1 Gao and Rouskas (2016) *In this model* $W = [w_{ij}]$ *is the communication between LoRa nodes as a traffic matrix, where data rate is represented by element* w_{ij} *from LoRa node (i to j).* r_i *represent the resource requirement which is associated with each LoRa node. With these definitions, partitioning the set of virtual nodes into k clusters so as to minimize the inter-cluster traffic can be formulated as the following integer linear program (ILP):*

$$\textbf{minimize} \sum_{k} \sum_{i.j} w_{i,j}(1 - y^{\frac{k}{ij}}) \tag{4.1}$$

$$\textbf{subject to} \sum_{i} r_i x^{\frac{k}{i}} \leq C_{apk} \qquad \forall k \tag{4.2}$$

$$\sum_{j} y^{\frac{i}{j}} = x^{\frac{k}{i}} \qquad \forall i, k \tag{4.3}$$

$$\sum_{k} x^{\frac{k}{i}} = 1 \qquad \forall i \tag{4.4}$$

$$x^{\frac{k}{i}} = 0, 1, y^{\frac{k}{ij}} = 0, 1 \tag{4.5}$$

Where h denotes the cluster and is associated with a capacity threshold C_{aph}. The binary variable $x^{\frac{k}{i}}$ ε 0,1 here indicates if LoRa node i is assigned to cluster k while binary variable $y^{\frac{k}{ij}}$ ε 0,1 binary variables indicates if virtual nodes i and j are both mapped onto cluster k.

Through the k clustering centroids, Theorem 1 optimize LoRa Gateway positioning to be geometrically closest to as many LoRa nodes as possible. The feature from this theorem also addressed the computation of the k highest points which is what improved algorithm also achieves where higher altitudes for LoRa Gateway placement create better Quality of Service (QoS) and network coverage. Furthermore, this is achieved through the positive correlation between evaluation of LoRa Gateways and their Line of Sight (LoS) coverage as defined by (Polak et al., 2021):

$$d \approx 3.57(\sqrt{\alpha h_1}) + \sqrt{\alpha h_2}) \tag{4.6}$$

Where α denotes the constant for earth's bulge and the distance between LoRa nodes and the Gateway is represented by d. Gateways are placed with h_1 antenna height towards a LoRa nodes placed at h_2 antenna height.

The purpose of the improved Gateway placement algorithm is a long-range transmission and to obtain the quantitative idea of how LoRaWAN respond and perform in the Gateway placement algorithm. Wireless networks are highly variable performance; therefore, exhaustive evaluation of performance is impractical in normal environment and laboratory conditions (Zhao and Govindan, 2003). Additionally, the performance of the algorithm also relies on the particular scenarios created. ADR algorithm in LoRa transmission is described in algorithm 1. This algorithm has the capability of modifying TP and SF in the network server. If the uplink transmission is unable to reach the Gateway, the algorithm increases the SF, the LoRa node can increase the uplink frame if downlink frame is not received within configurable number of frames. The probability of reaching the Gateway increases with the increase of transmission range and SF by the uplink transmission.

The improved LoRa Gateway placement algorithm is designed to employ a two phase scheme (*i.e.*, processing and validation) as shown in Figure 4.2. This design will help the Gateway placement algorithm to compute the optimal Gateway placement in a sequential order as follows:

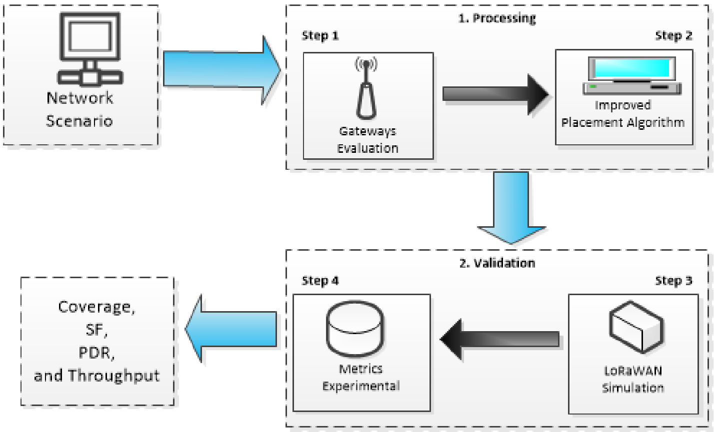

Figure 4.2: Improved Gateway Placement Algorithm and Phases Overview.

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In the first phase, after the network scenarios have been created, Gateways are evaluated in the process of classifying the number of IoT devices present in the network which includes LoRa nodes and LoRa Gateways. This method is similar to the one used in (Van den Abeele et al., 2017) and (Tibshirani et al., 2001). The algorithm used, with its time complexity of $O(n^2)$ has the capability of classifying the fractional degree of membership of each Gateway signal radius for each LoRa device. This helps the deployed LoRa devices to quickly identify the available channel to transmit their packets into the Gateway. Furthermore, when LoRa nodes experience the interference or loses connection for being in the range of n Gateways, they keep on transmitting packets using free channels to significantly minimise data loss.

In the second phase, with the LoRa Gateways positions, the optimal positions previously computed will be validated in a LoRa environment. In other words, as the basic LoRaWAN network requirements for proper functioning number of channels, CR, SF or even frequency all need to be included. In order for the LoRa Gateway placement algorithm to get the amount of packet lost due to interference, the number of packets received, the number of packets sent, and a number of lost packets due to channel unavailability, the LoRa Gateway positions must be imported and evaluated multiple times.

4.4 Implementation of Improved algorithm

LoRaWAN scenario has three parts by default. These parts includes the LoRa Gateway, the LoRa nodes and the network server. In this scenario, the improved Gateway placement algorithm generates a junction of several gateway positions. It is important to note that LoRa nodes in the simulation area are randomly distributed during the execution of Gateway placement as stated in (Metzger et al., 2019) and (Petrić et al., 2016). The LoRa nodes help to collect the data and transmit same via the LoRa Gateway to the network server, whereas LoRa Gateway has a circular coverage area with a radio channel.

4.5 Chapter Summary

This chapter described the design and implementation decision taken to develop an improved Gateway placement algorithm. The algorithm was specifically designed for best Gateway positioning in LoRa transmission network which was simulation based. These Gateways deployed in the network use the uni-directional and bi-directional transmission in order to receive and transmit the packets from or to. Improved Gateway placement algorithm was proposed due to the lack of existing algorithms to best position the Gateways and maximise the network throughput.

Improved algorithm adopted the integration features from other existing algorithms to solve Gateway placement problem and maximise the network connectivity whilst achieving a goal of low power transmission in the process. This approach allows the improved algorithm to not only find suitable candidate locations for the Gateway(s) but also improve the data rate, network throughput and maintain the connectivity in the network and LPWAN environment.

The LoRa Gateway is responsible for forwarding the packets between LoRa nodes and network server. Therefore, the improved Gateway placement algorithm operates with the LoRa modules to collaborate the behavior of nodes and Gateways on different levels from physical layer (PHY) to application layer. The results of low power consumption, low complexity and high robustness have all been demonstrated by the improved algorithm. This algorithm will serve as the basis for evaluating the performance of the network and improvement to the energy efficiency.

The next two chapters (5 and 6)describe the methods, the evaluation set up and measurements methodologies used for the various experiments that were conducted as part of the afore-mentioned evaluation. The details for simulation evaluation are provided.

Chapter 5

Design of simulation model

5.1 Chapter Overview

This chapter focuses on the detailed research and analysis methods that were undertaken in this study to gather research information and proffer a solution to the formulated problem. The design and implementation of LoRa gateway placement algorithm is implemented in a form of simulation. Design considerations and a description of the simulation will be followed by details on the various software and hardware elements. The simulation methodology and procedure are also discussed.

5.2 Software Configuration

The online open-source available tool was used to implement the simulator. The complete LoRa network simulation was built using these resources and the environment of adaptive required scenario was considered. The simulation environment allowed an exhaustive evaluation of performance and designing of topologies. The baseline software in this study include OMNET++, INET Framework and FLoRa Framework (Sanchez-Iborra et al., 2018).

(i) OMNET++

OMNET++ Integrated Development Environment (IDE) uses Eclipse as the main development platform and, enhances it with new functions such as wizards, views, new editors and so on. The new and/or re-configured existing models can be created in this IDE with the use of configuration files (.ini) and Network Description (NED). The obtained results were considered in order to provide a good performance analysis of the created network. The simulator took advantage of Git integration, C++ programming language and other open source tools and components. The model was defined and edited by the NED files by text or graphically. Both options created component classes, channels, compound modules and other objects features. Additionally, users also defined new set of parameters or random number seed and different scenarios through the use of ini files (Mauri, 2019).

This software provided the simulator with the capability to execute more than one process at the same time, hence the compiler is faster. While the simulation process is ongoing, the user is able to continue developing other parts of program due to parallel operations the simulator provides. The results are displayed in many forms once the simulation process was completed. They are preserved in scalar and vector (as a collection of immediate results) files. Other external tools such as python were available for results analysis and visualisation.

(ii) INET Framework

The capabilities of the simulator can be enhanced by adding new frameworks to OMNET++. INET includes protocols, agent, and many more other models to certify scenarios or protocols, redefine and create network. The supplied models in INET includes application communication, transport, network, link, and physical layers for different types of network communication such as Wireless Sensor Networks (WSN), ad-hoc, wireless, and wired. The operation of INET is based on exchanging messages between the LoRa modules.

(iii) FLoRa Framework

FLoRa and INET is a specific solution framework to test LoRa/LoRaWAN networks. Link and physical layer evaluation are enabled through FLoRa and define one or more gateways in the network. The communication in the network is bi-directional where LoRa nodes send frames defining the path for messages from destination (LoRa nodes to network server). FLoRa also has the capability of estimating the energy consumption and setting the main parameters for LoRa/LoRaWAN, such as the TP, CR, BW, CF, and SF, which influence the coverage of communication and data frame probability of frames collision. If the received power is greater than the power sensitivity (mainly depending on TP and SF), it is highly possible that a frame is correctly received as a LoRa transmission processed. For every LoRa nodes present in the network energy consumption is estimated via framework based on time taken by LoRa radio module in a specific state (i.e. transmit, receive, sleep, and off) and the value of TP (Mauri, 2019).

Furthermore, Semtech SX1272/73 datasheet provides a supply voltage of 3.3V for the consumption for each condition. Finally, a typical deployment does not usually consist only of LoRa end-nodes and LoRa gateway. For example, a backbone network is often included behind the LoRa gateway in simulations to reach a Network Server. In this study, when LoRa gateway received a LoRa frame, it encapsulated the frame into an EthernetIIFrame and transmitted it to the Network Server using the TCP / IP protocol stack, in particular the User Datagram (UDP) messages. This part was simulated mainly using the previously described INET modules. Network Server can discard duplicate packets if multiple LoRa gateway receive the same packet (Mauri, 2019). An overview of the software elements for the simulation is shown in Figure 5.1. Dynamic management of configuration parameters was supported in the network server and LoRa nodes through ADR. Lastly, LoRa physical layer accurate model was featured (with capture effect and collisions) since the statistics of every LoRa nodes deployed was evaluated.

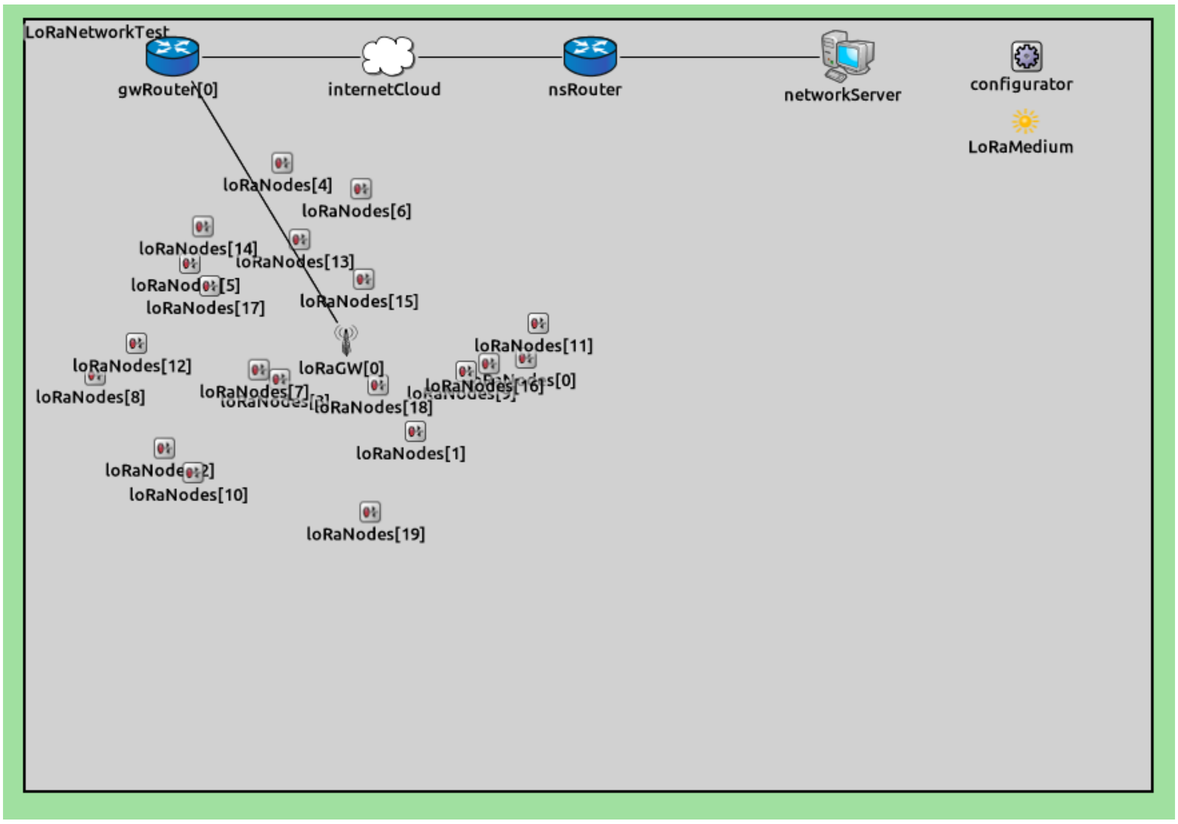

Figure 5.1: LoRa Modules.

5.3 Design and Layout

Literature review in the previous chapter (chapter 3) revealed that although there were various number of gateway algorithms proposed and implemented in LoRaWAN protocol using either simulation or testbeds. There is still a need to improve them for long-grange communication in LPWAN. The impact of range performance can be observed through the deployment of nodes in a fixed distance without even the need to relocate that particular node(s) constantly. Furthermore, continuous simultaneous of data collection is enabled through the permanent deployment of multiple nodes. In order to successfully perform a simulation of network, several software and hardware specification or requirements should be met. Gateway(s) can be easily placed in different positions in a robust and configurable system.

The LoRa simulation consists of two network scenarios one with 100 nodes and the other with 20 nodes. In both scenarios, Gateway(s) vary from one to two. This number will keep cost low, whilst maximizing the coverage in the network. All experiments were simulation based and run on virtual machine ubuntu 18.10 environment, the simulator integrated inet-4.1.1 with omnetpp v5.5.1. The simulator is written in C++ programming language. The Gateway(s) in both network scenarios were placed centrally in the simulation area and the LoRa devices distributed around them as shown in Figure 5.2 and Figure 5.3. The Gateway is responsible for facilitating communication in the network and it is connected to a network server.

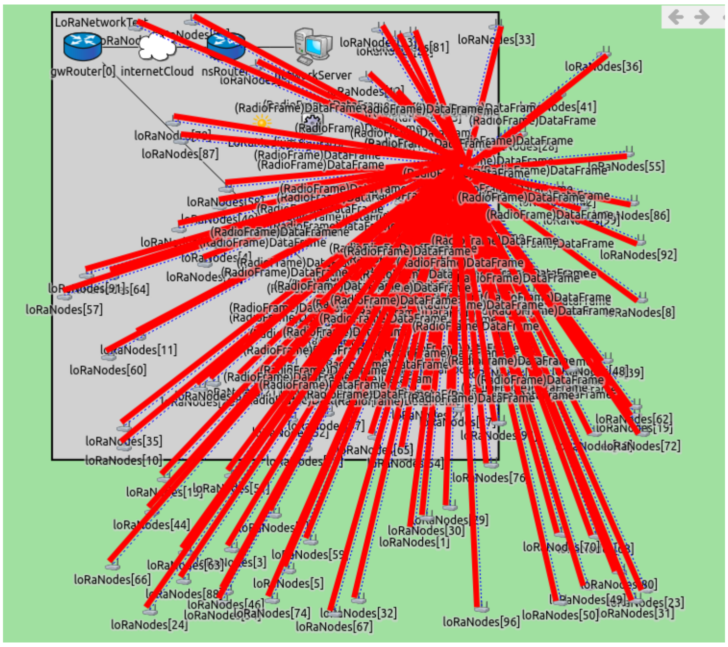

Figure 5.2: Example of first scenario with 100 nodes.

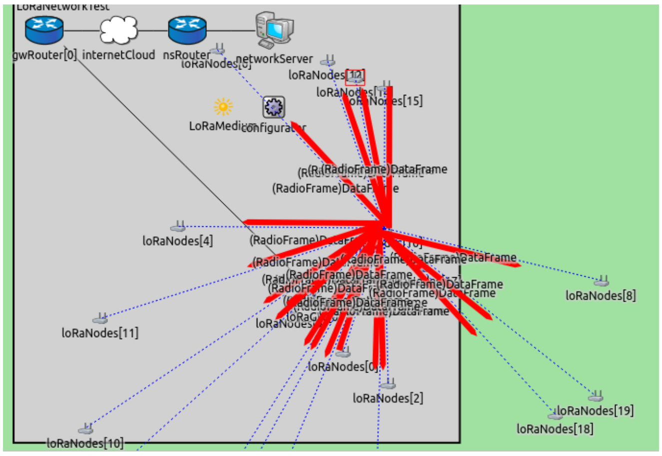

Figure 5.3: Example of second scenario with 20 nodes.

5.3.1 Topology and LoRa Devices

A star-of-stars topology approach was followed in this study, in which LoRa devices send or receive packets through the channel to or from one or more Gateway. The Gateway acts as a middle man between the LoRa devices and network server by forwarding packets via high throughput and a reliable link. It is assumed that at least one gateway will receive the packets and forward them to the network server after the end devices had sent them as illustrated in Figure 5.4.

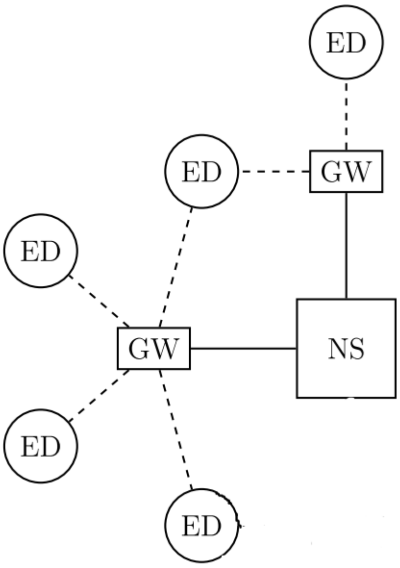

Figure 5.4: Example of LoRa network star-of-stars topology.

5.4 LoRa simulations framework

This section discusses the LoRa simulations in details including the configuration of LoRa devices deployed and their parameters. Framework for LoRa (FLoRa) carries out end-to-end simulations for LoRa network. The framework is based on a simulator called OMNET++ and takes advantage of INET framework components, with modules from network server, Gateway(s) and LoRa nodes FloRa which allows the creation of LoRa networks. ADR helps in the dynamic management of parameters configuration with the support of LoRa nodes and network server. Finally, for every LoRa node present in the network energy consumption statistic is collected and LoRa physical layer characterization is described (Sommer et al., 2010) and (Petajajarvi et al., 2015).

5.4.1 LoRa Links

In the LoRa physical layer transmission, parameters are configured through the support of FLoRa. Such parameters include TP, CR, BW, center frequency and SF. The occurrence of collision and transmission range are influenced by these parameters. For example, if the receiver sensitivity is less than the received power, the LoRa transmission is successful. The long-distance path loss equation below was used to model the transmission range, received power and receiver sensitivity by determining path loss based on distance between receiver and transmitter:

$$PL(d)=\overline{PL}(d_0)+10n\log(\frac{d}{d_0})+X_\sigma \tag{5.1}$$

where the mean path loss for distance d_0 is denoted by $\overline{PL}(d_0)$, $X\sigma$ and n represents zero-mean Gaussian distributed random variable and path loss exponent respectively. A transmission is regarded as successful if no interference occurred during LoRa transmission of packets. Furthermore, the assumption is made if two transmissions in orthogonal channel (meaning transmission of different SFs) do not collide. Lastly, the TP is calculated as: TP= 2dBm + 3dBm ×intuniform(0,4) and communication model was validated against the results (Sommer et al., 2010) and Mnguni et al. (2021).

The protocol stack of nodes,gateways and network server are shown in Figure 5.5. Gateway is responsible for forwarding messages between the nodes and network server, whereas the nodes and network server have an application layer.

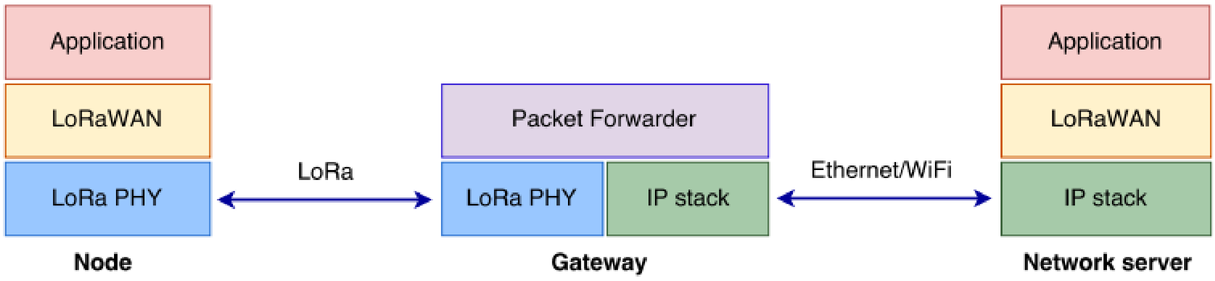

Figure 5.5: Corresponding protocol stack and available FLoRa modules Sommer et al. (2010).

5.4.2 Energy consumption module

In a particular state, the amount of time spent by LoRa radio determines the energy consumed. State-based energy consumer module is used to model energy expenditure. Sleep, receive and transmit form three main states of LoRa radio after receiving or transmitting a frame and the radio is switched to a sleep mode. The level of TP always controls the energy consumed in the transmit state (Bor et al., 2016; Bouguera et al., 2018; Kim et al., 2016).

5.4.3 The LoRa Module

A LoRa module was created with the intention to model the behaviour of LoRaWAN. This module plays a significant role in terms of modelling classes that work together to elaborate the behaviour of LoRa nodes and gateways on different levels, from the physical layer (PHY) to the application layer Ullah et al. (2012). Figure 5.6 describes some of the classes needed to stimulate the protocol stack on a LoRa device. Additionally, the aspect of the system such as the duty cycle limitations, correlation shadow interference and dense caused by the presence of buildings are also modelled by those classes representing a layer in a stack(*LoRaMac* and *LoRaPHY*). This study focuses more on LoRa gateway placement in LPWAN and the implementation of LoRa nodes and gateways (Magrin et al., 2017).

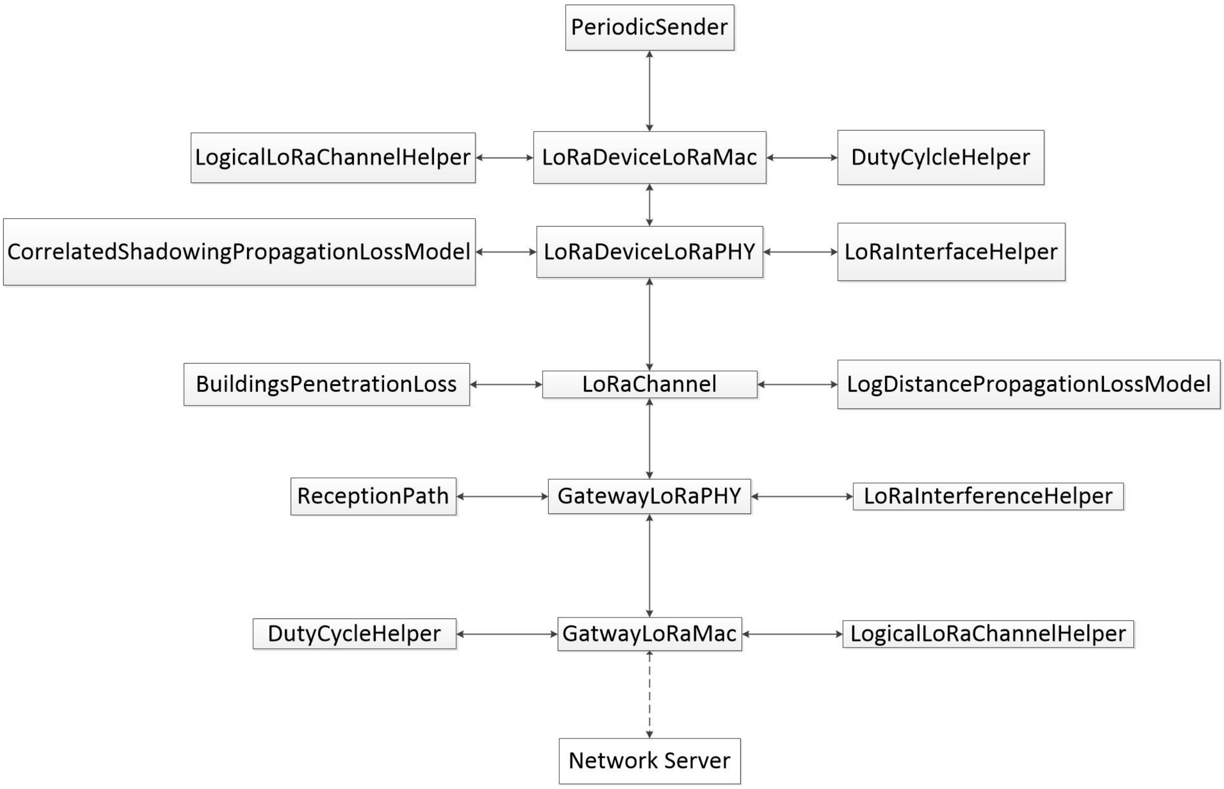

Figure 5.6: The LoRaWAN stack as it was represented in the LoRa module.

5.4.4 Periodic Sender

PeriodicSender is an application layer class which is found in a packet generator. A transmitted random packet delay is determined by the application transmission period. It also determines the event scheduled after transmission and can be configured as an attribute of the class. Furthermore, through transmission, the packet is handed down to the LoRa MAC layer from the application layer. *PeriodicSender* is responsible for the next transmission schedule and the revoking of packet. Packets will be sent via application until it stopped once a specific function is revoked Magrin (2016).

5.4.5 LoRaMac

MAC layer of a LoRaWAN device is modelled by the *LoRaMac* class. The *LogicalLoRaChannelHelper* object is used by *LoRaMac* class for tracing unused and available network channels to transmit data through, and it also provide clarity on duty cycle short comings forced by the regulations. This class is not capable of invading duty cycle rules and sending messages coming from the upper layer, but the

DutyCycleHelper class is responsible for maintaining various duty cycles on unique sub-bands and differentiates duty cycle logic from the class (Abdelfadeel et al., 2018). Furthermore, *GatewayLoRaMac* and *LoRaDeviceMac* subclasses were specifically created to implement the behaviours of LoRa device and Gateway respectively.

LoRaDeviceLoRaMac class handle the state of underlying PHY layer. In this class, device is defined and influences the behaviour of the LoRa nodes. The class ensures that the radio channel is correctly working when the receiver window needs to be opened. The procedure to send packet in the *LoRaNodesLoRaMac* class is described in algorithm 2, where packets are taken by MAC layer from application layer and passed to the underlying PHY layer. This algorithm also illustrate how transmission of packets is done from a random channel picked by LoRa nodes and at where the queue one packet is kept at a time Magrin (2016).

The *LoRaNodesLoRaMac* and *GatewayLoRaMac* are different since *GatewayLoRaMac* class implements a simpler forward only MAC layer. The interpretation of MAC commands is done by these two classes which are the *LoRaNodesLoRaMac* and *GatewayLoRaMac* (Goursaud and Gorce, 2015) A specific structure of LoRa packets is implemented as an extension of the basic packet class.

Algorithm 2 Procedure for packet process in *LoRaNodesLoRaMac* class.

```
Input: The packet variable contains the application-level payload
 Mac header and Frame added to the packet
 N denote number of channels available
 Channels = [1,...,N]
 Rearrange channels
shortestWaitingTime = ∞
 for every channel C in the channel lists
 t= Time taken on channel C, taken from DutyCycleHelper
 if t<shortestWaitingTime
 t=shortestWaitingTime
if t=0
 Send packet to the LoRa node's LoRaPHY class
Send notification of new transmission to DutyCycleHelper
return
Abort event sent previously
Schedule retransmission of packet after shortestWaitingTime seconds
Return
```

5.4.6 LoRaPHY

Physical layer of a Semtech LoRa device is modelled by the *LoRaPHY* class. SX1272 and SX1301 are amongst the LoRa chirps behaviour simulated by *LoRaPHY* class in LoRa nodes and Gateways, respectively. This class works hand in hand with MAC layer. For example, when the transmission occurs, LoRa nodes has to send the message to the Gateway and *LoRaPHY* takes packets from MAC layer to send it to an available channel. Additionally, the class has the responsibility to decide the channel correctly for the received packets obtained or not, using the interference and power LoRa nodes. *LoRaNodesLoRaPHY* and *GatewayLoRaPHY* are amongst the subclasses found in *LoRaPHY* class which explain in detail PHY layers of LoRa nodes and Gateways. *LoRaInterferenceHelper* class monitor the signal that is received by the LoRa nodes Magrin (2016).

LoRaNodesLoRaPHY receives the notification from *LoRaChannel* once the signal is received by the antenna. Algorithm 3 describes the process in detail. Initially, the add function is executed in *LoRaInterferenceHelper* with the aim of ensuring that the event class is created for signal. An event function provides every necessary information, such as SF, power transmission and time taken for signal to reach the antenna to perform the interference computations. An event is set to be scheduled off if the LoRa device has received the packets, and packets TP is compared to the device's sensitivity power. The procedure above is performed only if the underlying PHY is in its IDLE state where IDLE is the state of listening for incoming packets RC during reception of an incoming packet. Otherwise, the LoRa device transmits or receives reception of another packets, or sleeps Magrin (2016).

The implementation of *LoRaNodesLoRaPHY* is simpler than that of *GatewayLoRaPHY* since multiple receive paths need to be implemented. A variable list of *ReceptionPath* objects is featured in *GatewayLoRaPHY*; this class is called *LoRaChannel*. The procedure can be performed if there is a *ReceptionPath* listening to the channel of incoming packets. However, the receive path is certified as busy if transmission packets arriving are above the sensitivity power.

Algorithm 3 Beginning of reception of a packet.

```
Input: Packet = A received payload of the packet
Input: SF= Spreading factor of transmitting signal
Input: Sensitivity= minimum power (dBm) required to receive packet
Input: rxdBm = reception power of the signal
Input: d= time taken for the signal
 Sent notification to LoRaInterferenceHelper of the signal with SF
if state= IDLE
 if rxdBm < sensitivity
 return
else
 switch to RC state
 schedule for the termination of the reception of the packet after d
return
```

5.4.7 LoRa Channel

In LoRaWAN all devices including LoRa nodes and gateways share wireless channels which are modelled by the LoRaChannel class. PHY layer has the mandate of transmitting and delivering the packets to a set of *LoRaPHY* and *LoRaChannel* class is responsible for taking those packets, including a receive power computation. Send and receive methods are put in action by the *LoRaChannel* with the aim of allowing the interconnection between registered PHYs. SFs,PHY layer, channel number, TP and the duration. All play a vital role in the process of sending the messages in the channel after PHY calls a send function. PHYs list before calling this method is checked by the channel and for every LoRa node listening, a schedule receive event is created for those nodes to enable the transmission in the channel.

5.5 Hardware

In this section, Figure 5.7 shows the machine used for the process of simulation. An i7 intel core machine was used to take the advantage of its high speed processor.

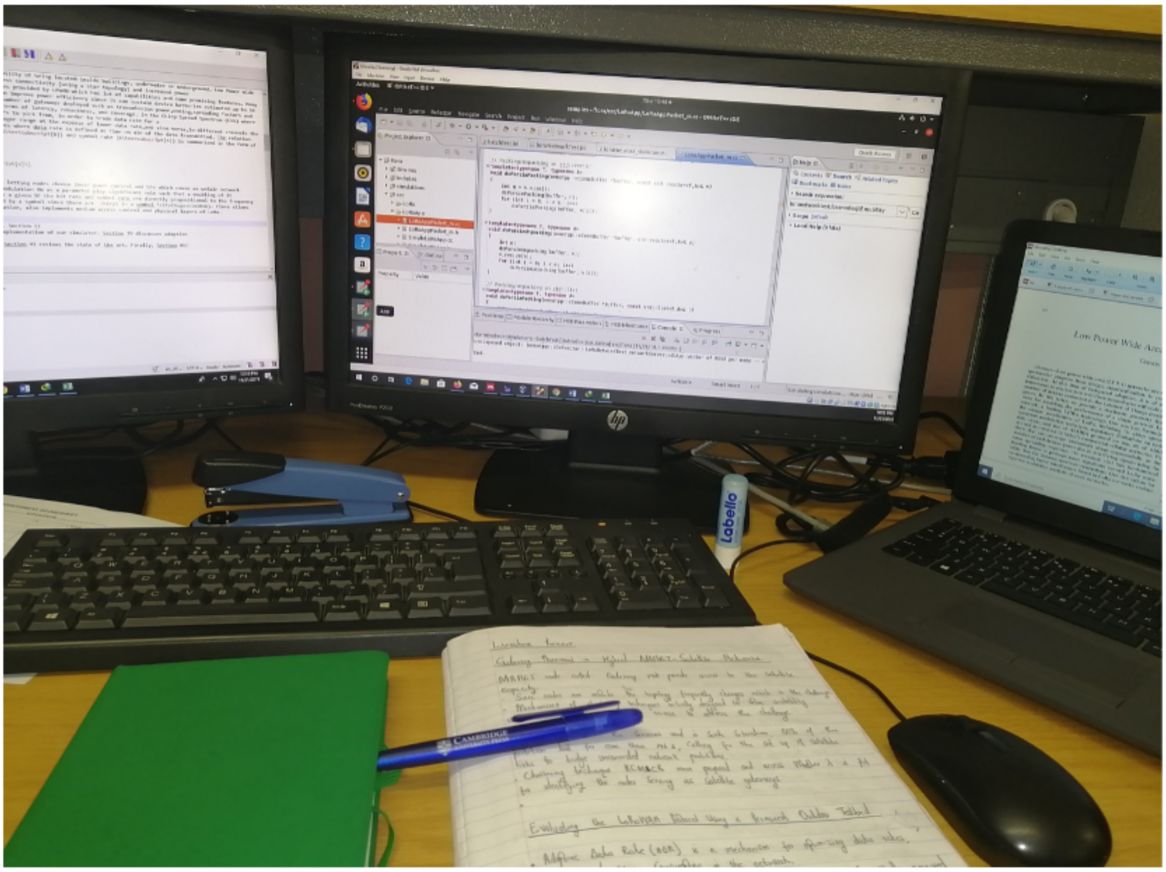

Figure 5.7: i7 intel core machine.

5.6 Simulation Scenario

The performance of LoRa networks was evaluated with the help of FloRa. Two simulation experiments were conducted. In the first one, a network of 100 nodes was created; it varied from 100 to 700 in steps of 100. For both experiments, the number of LoRa Gateway(s) varied from one to two, and for the LoRa physical layer, European environmental parameters were used as explained in Table 5.1. The second simulation consists of a 20 nodes network with different Gateways, where every LoRa node deployed picked an arbitrary TP and SF distributed within a permissible range.

INET framework played a significant role in modelling the backhaul network with a TP of 10 dBm and no packet loss. In the simulation, a typical sensing application was considered. After distribution time, each LoRa node sent a 20-byte packet with a mean of 1,000s. The size of the deployment area was set to $500mby500m$ for the first scenario, $10000mby10000m$ for the second scenario. All the deployed LoRa devices were

Table 5.1: Parameters for Simulation

Parameters	Value(s)
Transmission Power	2 dBm to 14 dBm
Spreading Factor	7 to 12
Code Rate	4/8
Bandwidth	125 kHz
Carrier Frequency	868 MHz

located within the square region to communicate with the Gateway(s), and the nodes were randomly placed. The simulated time for both experiments lasted one day, and ten iterations were run for accuracy of the results. LoRa networks performance was evaluated with and without ADR. Both at the network server and the nodes mechanisms were disabled in networks with no ADR. ADR-node ran on all variants of ADR and nodes at the network server when the ADR was enabled.

5.6.1 Simulation Script

Algorithm 4 Simulation Script.

```
Input: Number of Gateways.
Input: Number of LoRaNodes.
Input: Radius for deployment area.
Assign UDPApps in LoRaGW, LoRaNodes, and Server.
Create packet forwarder for all ports
Sim-time-limit = 1d
Warm-up period =5h
Create LoRaNodes features.
ADR inNode = True/False
InitialLoRaSF= (7,12)
InitialLoRaBW= (125KHz)
InitialLoRaCR= (4)
InitialLoRaTP= (2dBm + 3dBm * uniform (0,4))
Setup GW features
Start the simulation
Save the simulation results
return
```

Algorithm 4 provide a detailed explanation of the main steps followed in the simulation script. Different scenarios were presented in different scripts for different purposes.

LoRaNetworkTest.in and betTest.in files defined the scenarios. Scenarios consisted of certain features including LoRa Nodes, Gateway(s), and a network server. For every network scenario created, LoRaNodes were randomly distributed in the deployment area keeping in mind a radius. TP and SFs were allocated for every node from available settings. ADR was disabled and enabled where necessary in the nodes and network server. A day was configured as the simulation time limit with a warm-up period of 5 hours. CloudDelay.xml file consist of backhaul network configuration and its link on package.ned file.

5.6.2 Metrics and Variables

A lot of variables were required to make the simulation described above possible. The performance of LoRa networks can be seen through the adjustment of these variables. Here are some of the notable variables:

- Network scale: The higher the number of LoRa nodes in the network, the higher the probability of noise interference due to congestion. The deployment of gateway in the area will play a vital role in terms of nodes coverage since the device with heavy shadowing depends on higher gateway density to communicate.
- Application layer traffic generated model: collision between packets will rise at a lower message inter-arrival. The destructive interference might increase due to synchronicity in packets departure time.
- Path loss model components: the Gateway range coverage is affected by these models i.e., less dense buildings decrease the loss computed by the channel and enables a long-range traveling of receiver transmitter signal before they fall short under the sensitivity of the receiver.

  Similarly, LoRaWAN system is responsible for the evaluation of different matrices:
- Distribution of SF: this is how the propagation loss model affect the SF and its distribution at various distances from the gateway.
- Network throughput: considering the performance of the whole system, the main focus in this case will be a probability of successful packet delivery and network performance as well.

5.7 Chapter Summary

The procedure followed to carry out the simulation for LoRaWAN is presented. An overview of the simulation setup, how the LoRa nodes were placed, various parameters, software and hardware parts were all provided. This was followed by simulation scenarios, simulation script, metrics and the variable used.

The simulation scenarios created for different networks were presented in Section 5.6. The networks consist of 20 and 100 nodes for the same reason of evaluating the Improved algorithm when the network is big or small. The Gateways were also varied from one to two for performance reasons and to address the placement of Gateway issue. However, due to power limits on the machines used, it could not go above 2 Gateways and the size of networks were limited due to same reasons. The insight of the simulator configuration was also given with all parameters used and the types of area chosen for specific reasons are explained. The simulation time for the experiment were also detailed in this section.

The simulation scripts were given in this chapter to give insight into what transpired prior to the results. The matrices and variables were briefly explained. Some of the matrices include network throughput, distribution of SFs, path loss model and application layer.

Chapter 6

Experimental Results

6.1 Chapter overview

This chapter presents the results obtained from the simulations performed using the LoRa modules described in the previous chapter (Chapter 5), and results analysis. SFs and data rate are vital in the performance of the metrics used in this study. These metrics include PDR, power consumption, latency and Gateway coverage. The impact of payload, ADR, and Acknowledgments (ACK) were investigated in the various scenarios created.

The various metrics obtained in this study are analysed in this chapter with the help of LoRa modules added to Framework for LoRa (FLoRa). The first results to be evaluated is that of the Improved Gateway placement algorithm coverage followed by SF impact and its allocation. Then, a traffic and environment model are realistically modelled in the network set up with the aim of evaluating probability of packet loss in LoRaWAN. Other experiments such as energy consumption were performed to validate the impact of the number of Gateways in the network and SFs. Lastly, the network throughput for some performance network metrics like PDR ratio was explored.

6.2 Gateway Placement

Since Improved Gateway Placement uses random distribution, the results are bounded to have a certain variety. For that reason, all parameters of the algorithm are fixed ($r = 3.5km$) the set of (20 and 100 LoRa nodes) and the set of Gateway position candidates.

Figures 6.1 and 6.2 show the two distributions of nodes around the Gateway(s). One set of networks consisted of 20 LoRa nodes and the other 100 LoRa nodes with the intention to see the behaviour of Improved Gateway placement algorithm in a scalable network.

To analyse the result variance, we did ten iterations for accuracy of the same scenario, with regards to the number of LoRa nodes interfering each other according to the algorithm and also with regards to the number of LoRa Gateways per placement.

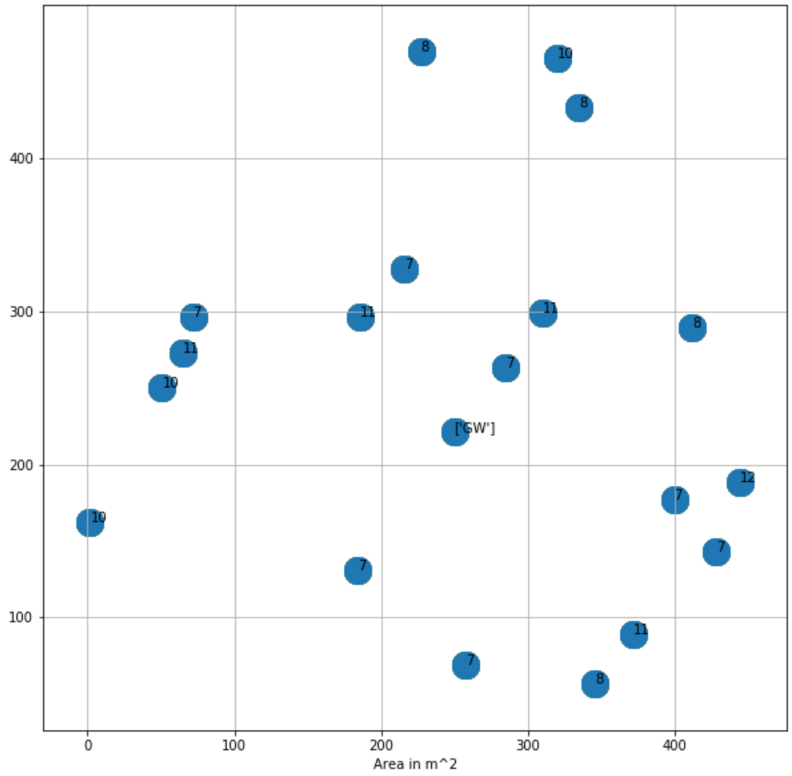

Figure 6.1: An example 20 nodes distribution around the Gateway.

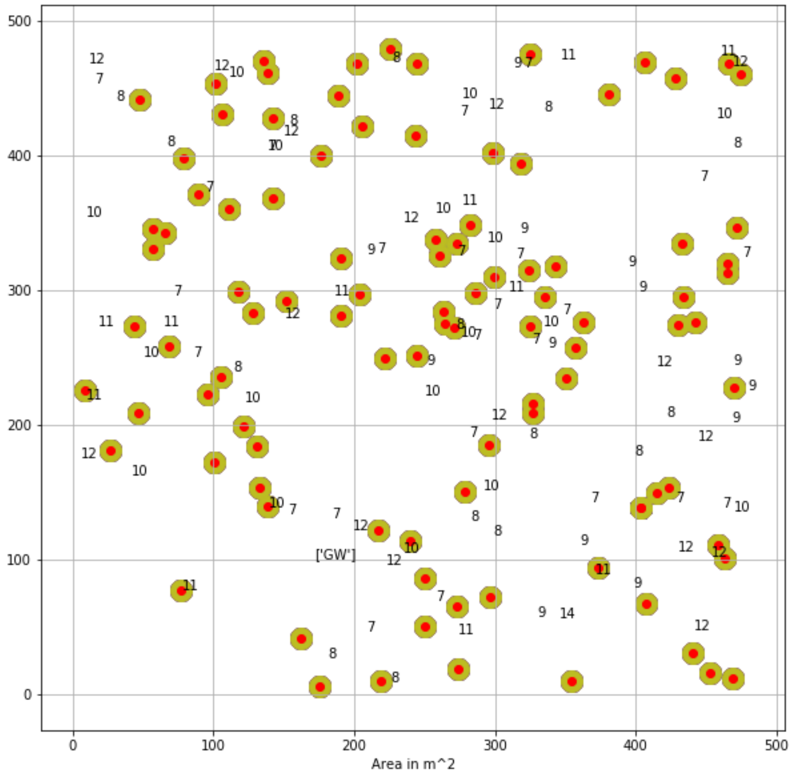

Figure 6.2: An example 100 nodes distribution around the Gateway.

6.3 Gateway Placement Algorithm Coverage

6.3.1 Coverage Criteria

The PDR was calculated to characterise coverage at each location. The ratio of successfully received packets at the network server over a total number of transmitted packets by LoRa device is called PDR. To examine the coverage of Improved Gateway placement algorithm, a PDR was calculated at each location of Gateway(s). Two (2) different network scenarios with LoRa nodes operating over different channels were used to simultaneously transmit packets. Each node transmits over 200 packets back-to-back. The average PDR is computed at each location using the calculated PDR of all end nodes. For the case of exposition, we only present the measurements results of eight locations identified in Table 6.1 as L1 to L8.

Table 6.1: Simulation coverage results

	Average PDR (%)	
Locations	G1	G2
L1	54.88	71.52
L2	60.28	54.49
L3	42.37	64.59
L4	43.76	89.18
L5	96.37	38.34
L6	79.17	52.89
L7	56.80	92.56
L8	7.10	8.71

6.3.2 Simulation measurements

The simulation measurements were conducted with the intention to evaluate coverage at a number of locations. To visualize the network coverage, we imposed the PDR results for the Gateways to create a heatmap of the aggregate network coverage across all Gateways, as shown in Figure 6.3.

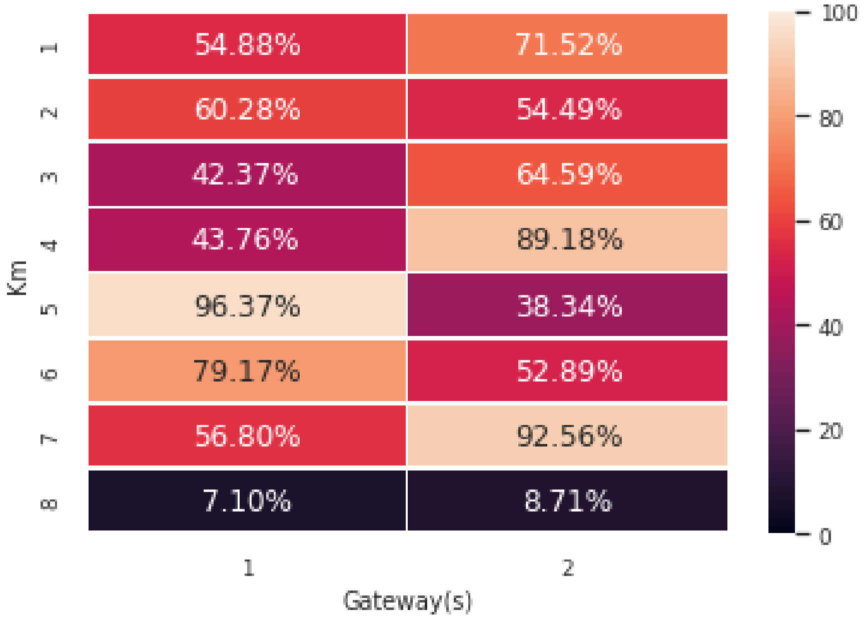

Figure 6.3: Network coverage heatmap.

The improved Gateway placement obtained an average of 92% PDR at a distance of $7Km$ between L3 location and Gateway G2 as shown in Table 6.1. At the same time, we see that even though the LoRa nodes were randomly placed closer to the Gateways in the network, the coverage of the network extends far beyond the edges of that particular area. In conclusion, it was observed that with more optimal Gateway placement, even two Gateways would be enough to cover an area with a radius of ($r = 3.5km$). The results confirm that effective long-range communication ($\geq 12Km$) can be achieved using LoRaWAN even in urban environments.

6.4 Spreading factor performance.

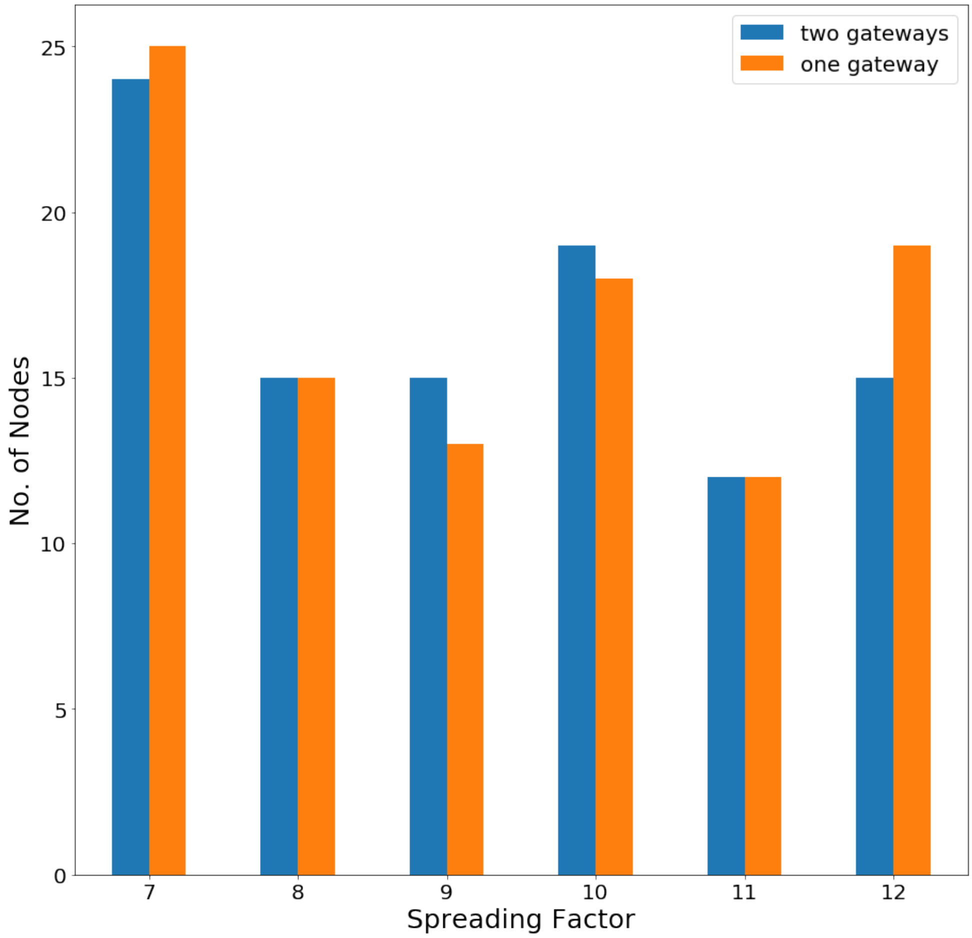

Figure 6.4: Comparison of the number of nodes of each SF.

Initially, the performance of networks with ADR was evaluated than followed by the analysis impact of the algorithm implemented for SF allocation. Next, we compared the performance of the algorithm if the network had one or two Gateways. Finally, the evaluation of energy efficiency was conducted in the algorithm 1.

Figure 6.4. shows the average number of nodes allocated to each SFs in different networks. Each network consists of 100 nodes with one or two Gateway(s). It is observed that most nodes were assigned to the lowest SF number 7 in both scenarios, indicating that most

nodes were close to the Gateway(s). A SF of 7 allows nodes to take as little time on air as possible to communicate with the Gateway(s). However, the possibility of collision between the packets is more likely to increase when the number of nodes with the same SF increases drastically. The same number of nodes were observed in SFs of 8 and 11 for both scenarios. The TP was kept constant throughout the simulation. However, in certain areas, it was observed that Gateway and nodes can only communicate if transmission occurs at a high SF and high TP.

Since there were different kinds of simulation performed for different purposes, Figure 6.4 showed a behaviour of the network or nodes in different conditions one with 2 Gateways and the other with 1. For both simulations it was observed that an average of 25% were occupied by nodes using SF7 in both scenarios with the least network using SF11 to transmit occupying almost an average of 12%, the SFs ranges from SF ε7,...,12. To set the SF for every LoRa nodes is very essential regardless of the medium access contention and to make sure that each nodes meets the standard given target of the PDR (Caillouet et al., 2019) and Reynders et al. (2017).

It was initially assumed that nodes consist of the same traffic intensity in the cell capacity. These kinds of experiments shows how distance can impact the signal strength and transmission as a whole, allocating more than one Gateway in a network can definitely increase packet success probability. However, it might be very expensive to deploy since these LoRa devices are not easily accessible or cheap which is why few Gateways are possible need to be deployed to obtain a maximum coverage. Through the experiments it was found that due to constructive or destructive unwanted signals, a node placed further away from the Gateway has a slightly increased chance of performing better than the one placed near.

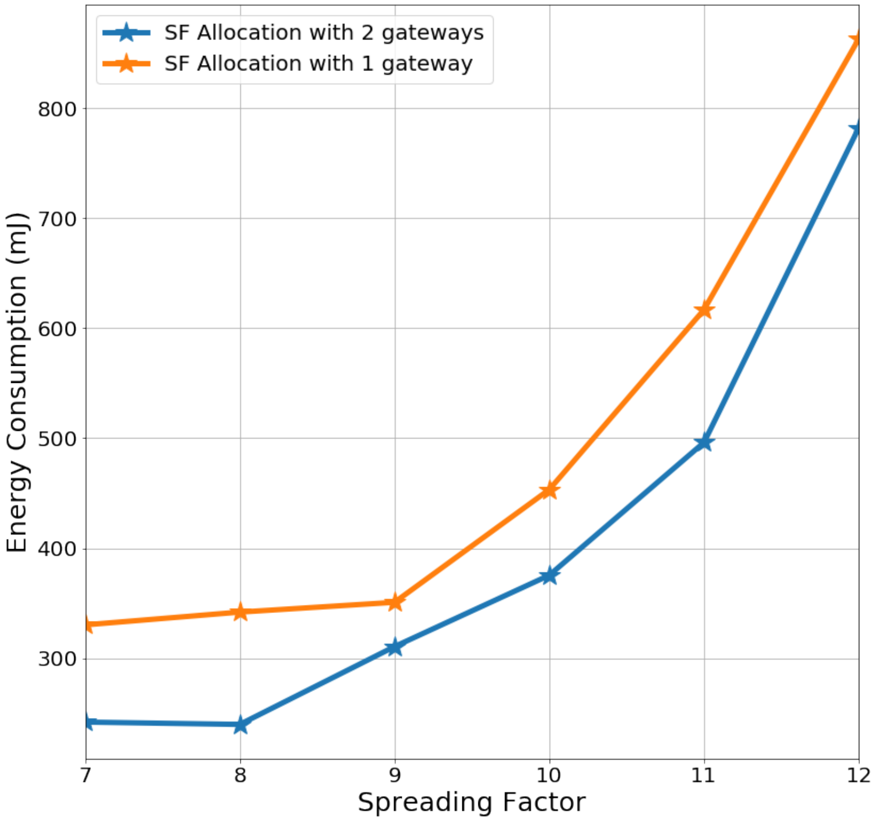

Figure 6.5: Energy consumed by nodes in each SFs.

Figure 6.5 shows the energy consumed by nodes transmitting data in different SFs. As expected, the SF of 12 has the highest amount of energy consumption in both cases. BW channel was set to 125 kHz throughout the simulation. Nodes assigned to SF of 12 consumed a high amount of energy due to transmission distance. The higher the SF, the more time taken to transmit a packet which resulted in high energy consumption during the process. The increase of packet transmission is influenced by the increasing number of encoding bits which allows radio module to consume more power. The SF with one Gateway consumed more energy when compared to SF with two Gateways. Energy consumed in both scenarios increased as the SF increased. The increase in energy consumption was due to the lack of available Gateways to transmit in a network with one Gateway.

The distance is independent of the constructive or destructive effects of multipath on the signal, but rather dependent on the obstructive that occur between the Gateway and the node (Baccour et al., 2012). The impact of SF was also seen against energy consumption in Figure 6.5 which shows that placing more than one Gateway still proves to have certain advantages over the drawbacks of affordability. In the two compared networks, SF12 had the highest amount of energy consumed and this was caused by many factors such as distance and time taken to transmit from the source to the destination. However, the figure also proves that indeed the network with 1 Gateway consumed much energy which averaged to 0.21% more than the one with 2 Gateways. This is because the nodes must wait for an unused channel or transmitter that are far off while looking for the destination.

The biggest impact in the LoRa network performance could be imposed by the settings of sub-optimal, whist another effect on LoRa nodes is certainly from the distance. Energy consumption in this study helped to evaluate the feasibility of LPWAN updates chips produced by different companies such as Semtech since LPWAN devices need to operate multiple years on a single battery charger(Ruckebusch et al., 2018).

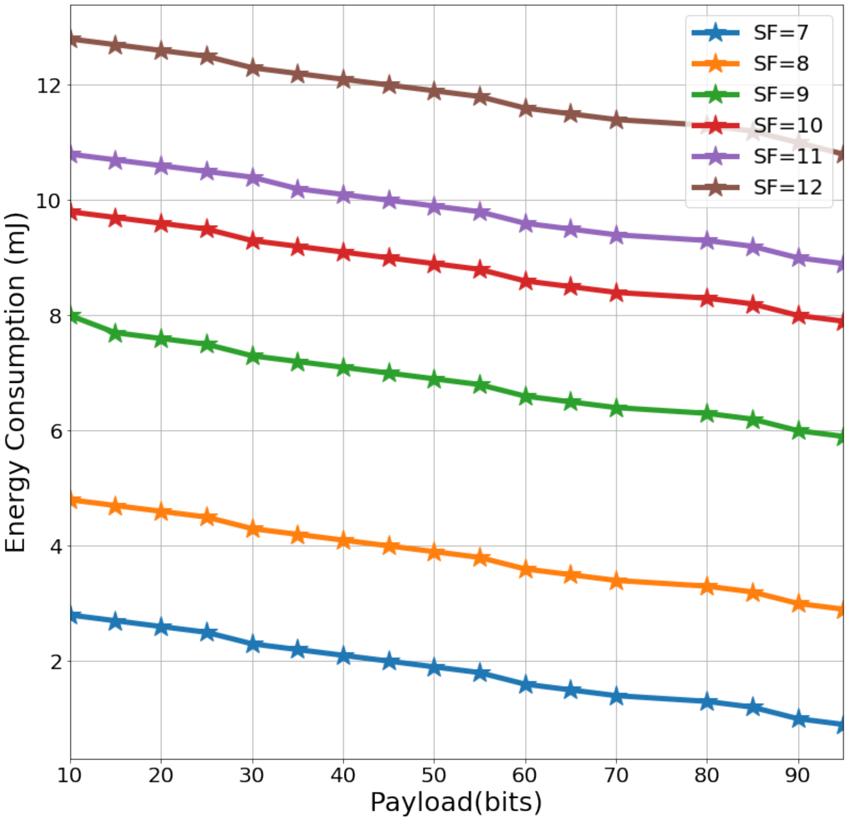

Figure 6.6: Energy consumed per useful bits at different SFs.

Figure 6.6 represents the energy consumed per useful bits at different SFs as a function of the payload. It is observed that with the increase of useful bits in the network, the energy consumption decreases. The energy consumed depends on the number of SF, i.e., if a node uses a SF of 12 to transmit packets, the time on-air will increase since the longer the distance, the more time it takes to transmit which results in an increase of energy consumption. If the node is closer to the Gateway, the SF of 7 will be picked for packet transmission depending on how near it is. In that case, less time will be taken on air due to the short travel distance which decreases the energy consumption as the useful payload bits increases. It is noted that energy consumed and the time on-air increased with the decrease of the CR, where the CR denotes a useful number of bits or transmission bits.

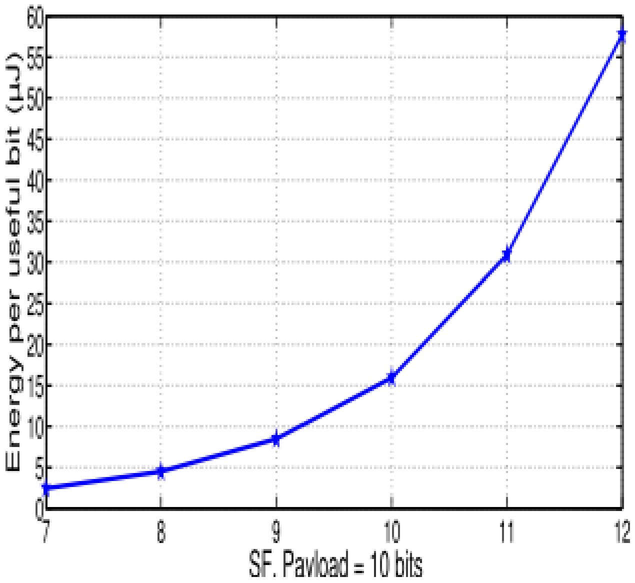

Figure 6.7: Evolution of energy per useful bit as a function of SF. Bouguera et al. (2018).

Another observation of this study is the amount of energy consumed per useful bits as a function of payload(bits) at different SFs that ranges from ε7,...,12. As Figure 6.6 shows the trend of different SFs and energy consumed per useful bits against payload bits, it is observed that at a certain rate when a payload bit increases, the energy consumption is affected by that since it also decreases. Figure 6.7 supports our research the the evolution of SF against energy per useful bits takes the hyperbolic trend with a $Payload = 10bits$, which states that more time is taken to transmit packets with a greater value of SF. Energy per useful bits increases as the value of SF increases. This is completely contrary to the payload bits since energy per useful bits decreases as it increases Nolan et al. (2016) and Buyukakkaslar et al. (2017).

However, useful bit is not only the factor for decreasing energy since the value of SF also contributes to the decrease of energy consumed by LoRa networks due to packet transmission time taken. In this study, we did not focus on CR but we did specify in Section 6.4 that the CR used for this improved algorithm simulation is $CR = \frac{4}{8}$. Therefore, again this parameter helps us to see the behaviour of our network since the consumed energy and time on air increases with the decrease of CR.

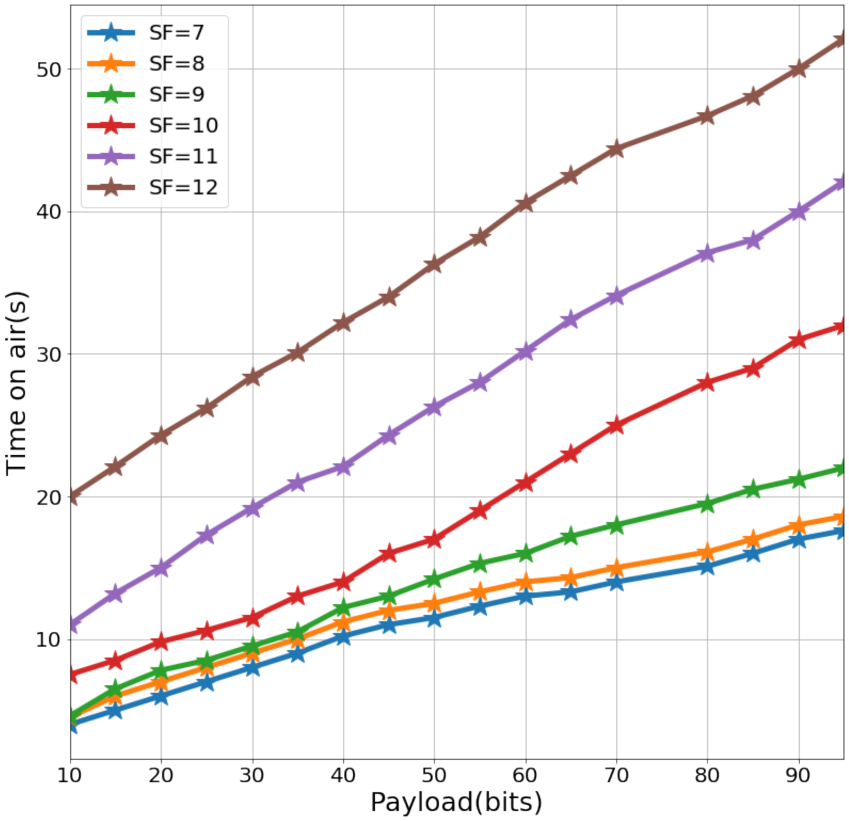

Figure 6.8: Energy consumed per payload bits at different SFs.

Figure 6.8 shows how time on-air, payload and SFs have strongly impacted the packet transmission from nodes to the Gateway(s). It is observed that time on-air increases as the number of Sf increases. SF of 12 has the highest amount of time on-air due to distance between nodes and the Gateways. There was a minor difference time on-air between the nodes used a SF of 7 and 8 which means the distance between those two SFs to the Gateway was almost equal for every channel picked up. Every step up in SF doubles the time on-air for the same amount of data to be transmitted, the longer the time on-air results in fewer data transmitted per unit of time with the same BW Potéreau et al. (2018).

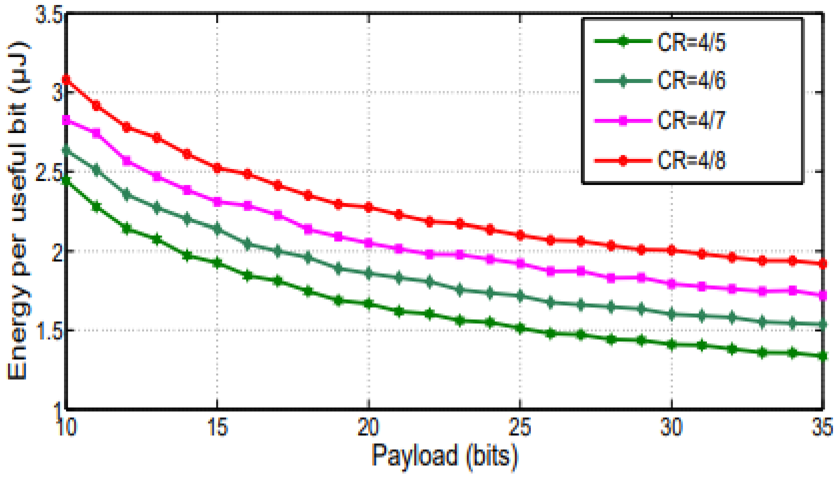

Figure 6.9: CR effect on the consumed energy SF=7 Bouguera et al. (2018).

This study conforms with previously conducted studies where the results obtained agreed that the optimization of LoRa parameters such as payload size, CR and SFs play a significant role in terms of mitigating energy consumed by the LoRa nodes. Figure 6.9 shows the graph of energy per useful bit against payload at a different CR, where energy consumed at $CR = \frac{4}{8}$ is slightly higher than the rest because of the distance and energy consumed. In our study, the CR was kept constant due to the performance of the Improved algorithm implemented.

The study also noted that both energy consumption where CR has an impact and time-on-air where the increase of packet transmission was caused by increasing number of encoding bits allowed more power to be consumed on radio module.

6.5 Packet Deliver Ratio (PDR)

To characterise the coverage of every LoRa node in the network, PDR for each node was calculated. A ratio of a successfully received data packets over a totally sent data packets is called PDR. Equation 6.1 is used to calculate PDR for each node:

$$PDR = \frac{Packetsreceived}{Packettransmitted} * 100 \tag{6.1}$$

In some cases, the node disconnect from the network and tries to reconnects at a later stage. Most of these packets might not be successfully delivered to the Gateway after failing to re-join the network. Therefore, equation 6.1 defines PDR solely focusing on data packets and thus does not reflect in anyway the success ratio of join-request. Furthermore, an alternative definition is not just data packets that will be included in the equation above but all available packets. Therefore, when the calculation is performed in the simulation using the equation, a minor error will be observed compared to that simulation. PDR equation does not include join request because they are tracked manually in the LoRa nodes as gateway will be aware of any unsuccessful join request and only start logging a LoRa nodes once it has successfully joined.

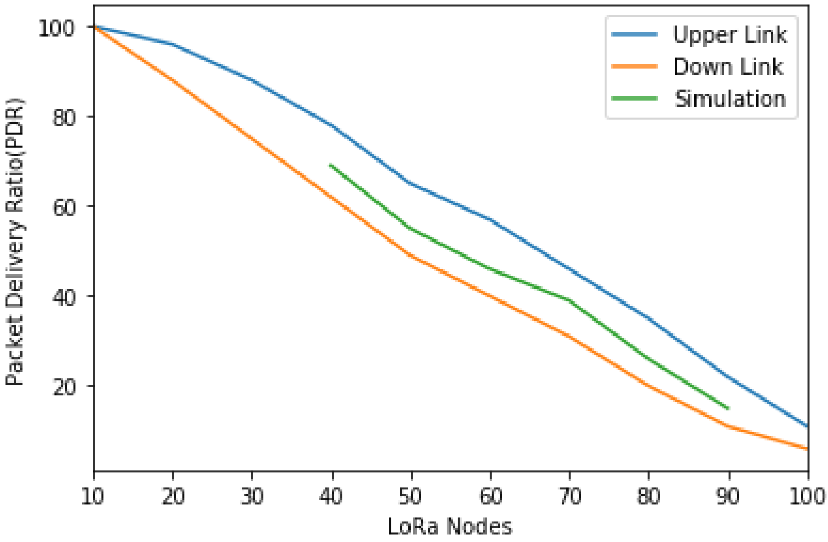

Figure 6.10: Successful delivery ratio probability experimental dependence.

Figure 6.10 illustrate the experimental dependence of the probability of successful delivery on the number of devices. The simulation consists of two links: upper and down links. The blue line represents the upper link of theoretical value PDR. While the orange line represents the down link of theoretical value of PDR and the green line shows the experimental results of the actual results. From this simulation, it is observed that the experimental value is close to the upper link theoretical value due to congestion in the down link which leads to massive packet loss as the network expands.

Another consideration, which we also examined in the study is the performance of the long-range nodes in the simulation process of the network by calculating PDR for packets sent from or to the Gateway (uplink/downlink traffic) and compared them with the actual simulated PDR. The connectivity amount differs between downlink and the uplink since the wireless sensor networks are known to have the link asymmetric (Baccour et al., 2012). Therefore, in each experiment, the calculated PDR is a reflection of downlink network performance and uplink network performance would differ. Downlink network transmission is allowed in the LoRaWAN transmission protocol, but to ensure that the network overall performance does not suffer or get affected in terms of performance these should be kept to the minimum. The network should be monitored very closely to ensure that the connectivity levels are acceptable for the downlink and uplink traffic when a LoRaWAN is deployed. Firmware over the air updates requires that the downlink performance is sufficient.

The results obtained through the simulation is shown in Figure 6.10. It was observed that for both the upper link and down link, the PDR percentage drops as the network expands at a different level including those of simulation. Although this should be the trend for the calculated PDR of a network with different LoRa node our Improved algorithm appears to give the better performance compared to other algorithms used before. In (Ilderyakov and Stepanov, 2019), the method used did not allow the use of many LoRa devices to perform a PDR for examining the performance. Whereas with our algorithm we managed to get a maximum of 100% PDR with a network of 10 devices for both uplink and downlink and around 61% for our experimental simulation PDR. As mentioned before, the increase of the network results in a decrease of PDR, therefore, we got less than 20% of PDR when our network consisted of 100 devices.

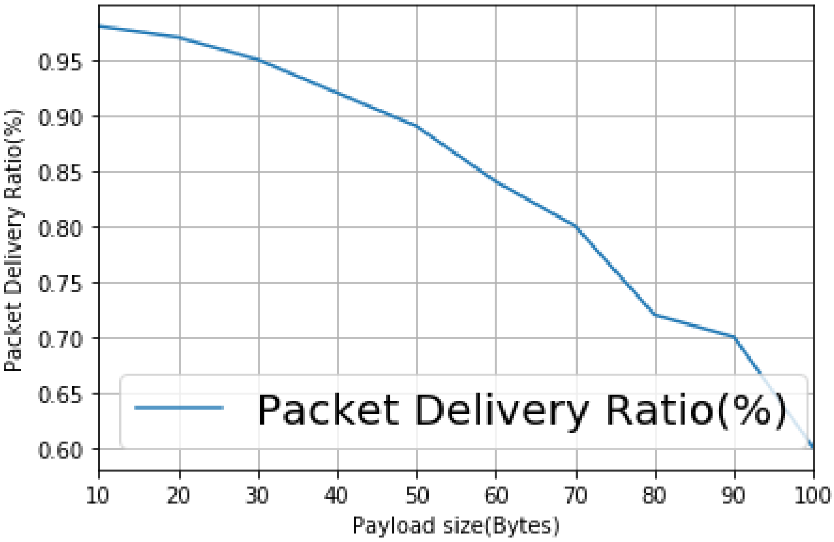

Figure 6.11: PDR versus payload size for a 100 LoRa nodes.

The variation of the payload size ranged from 10 Bytes to 100 Bytes, with a transmission rate of 1 packet per second for each LoRa nodes deployed in the network. According to the results obtained as explained in Figure 6.11, it was observed that to obtain at least 0.9% of PDR, payload size should be kept under 45 Bytes with a 125 kHz BW and CR of 4/5. This was an improved performance as compared to the study conducted by (Barriquello et al., 2017) which was done in a different environment.

PDR can be evaluated against payload size. In our experiments we observed how the payload affects the energy consumption of LaRa networks. Therefore, in this section we discuss how PDR is impacted by the payload size. Payload size is the average ratio between total number of packets transmitted by LoRa devices and the total number of packets received by the Gateways during a period of time Bor et al. (2016) and Zhao and Govindan (2003).

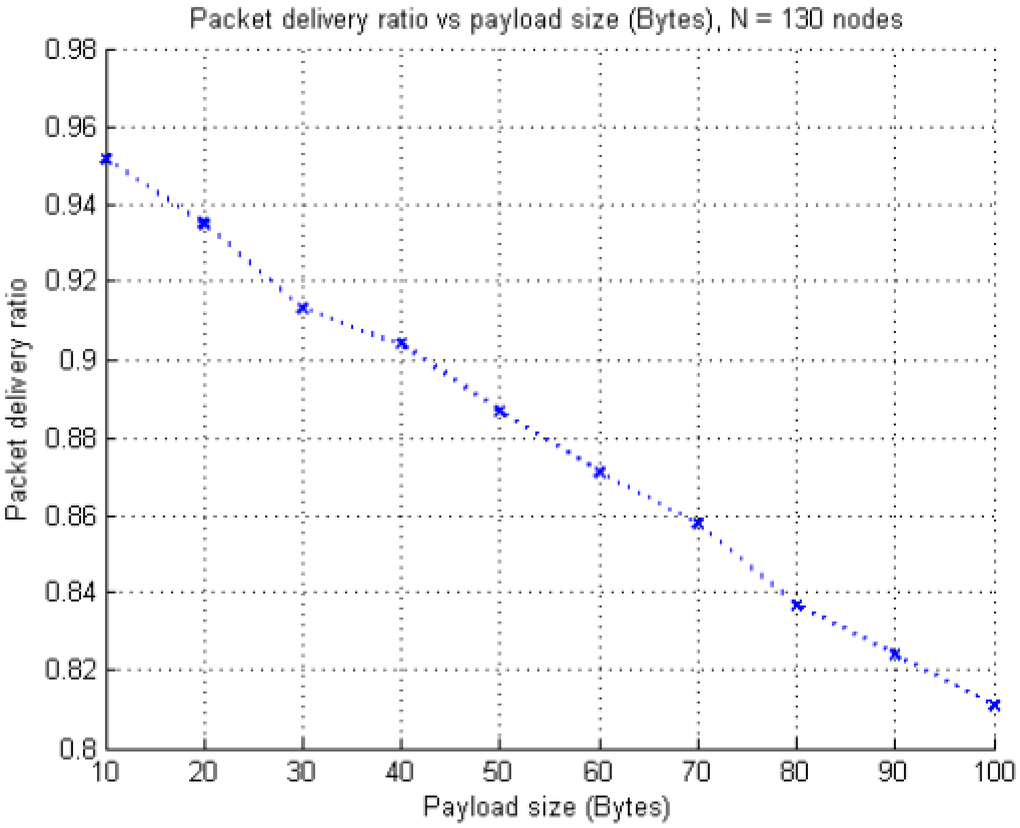

Figure 6.12: payload size vs PDR. Barriquello et al. (2017).

Even though the experiments were conducted using different simulators: one with LoRa simulator and the other with FLoRa. Figure 6.12 shows the results of PDR against the payload size which was done by scholars in (Barriquello et al., 2017). In this study, for a packet rate of 1 packet per minute, a payload size was varied from $10B$ to $130B$ which helped them to conclude that a delivery ratio is provided by a small number of packets. The algorithm used in our study showed an improvement of almost 0.19% compared to this study in terms of PDR since at 10 nodes they observed a delivery ratio of 0.95% which is less than 0.97% at 10 LoRa nodes.

The results observed in these two experiments were different even though some parameters such as CR and BW were the same. Furthermore, the study also agreed with our study that the delivery ratio increases with the increase of reporting time since less collision takes place in the process see (Figure 6.13).

In this study (Barriquello et al., 2017) they chose rural areas as the deployment area and 90% of their observation was obtained under 40 nodes. The transmission of packet occurred once in every minute which was slower than the expected normal time.

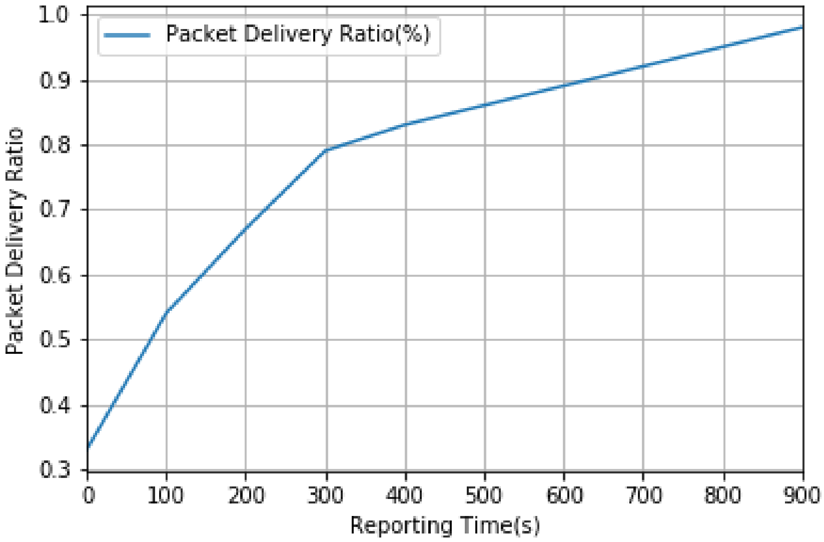

Figure 6.13: PDR versus reporting time (in second).

Figure 6.13 shows the influence of the reporting time on the PDR. For every LoRa nodes the reporting time was varied from 0 second to 900 seconds. The results clearly states that the PDR improves exponentially as the reporting time increases; the longer the time it takes for packet transmission the less network congestion which leads to the increasing PDR. It is observed that, by keeping the reporting time above 600 seconds, you find at least a PDR of more than 90.0% percent. Furthermore, up to almost 99.0% of the PDR observed in the network before the reporting time reached 900 seconds for transmission unit.

This is an enormous improvement on the transmission rate by the algorithm implemented in this study as compared to the existing one where most of them enable the network to reach a percentage of 90.0% once the reporting time nearly clocked 700 seconds with less LoRa nodes deployed in the networks compared to the 100 LoRa nodes used in this study. Furthermore, this subsection of PDR gave us a clear indication of where exactly the Gateway(s) should be placed in the network in order to maximize the network coverage and reduce the amount of time taken for every packet transmission being done.

6.6 Network performance evaluation

In this section we analysed and evaluated the network performance through the packet success probability and network throughput. The metrics used were influenced by the LoRa modules added in FLoRa for LoRaWAN simulation networks. The first step was to evaluate and visualize the results obtained for network throughput for performance purposes. The second step was to evaluate the success probability of the packet sent for every network scenario created in a LoRaWAN communication protocol. Some of the experiments were conducted based on the SFs transmission range and how SF influences the packet success rate.

6.6.1 Throughput Performance

The network throughput in this simulation campaign was characterised by S as a function offered by network traffic G where the function aims to evaluate network throughput. The network scenarios were divided into two as mentioned in Chapter 3: one with a single Gateway (GW) and the other with two Gateways and the LoRa nodes distributed around those GWs. In this equation, N denotes LoRa nodes placed around GW at a chosen radius r from the simulator. The value of radius is chosen based on SF=12, since r is the maximum range where LoRa nodes and GWs can transmit packet using SF=12 when considering a propagation loss. Multiple LoRa channels were considered for this simulation section performance, for all simulations measuring throughput the Gateway was configured to only have one receive path enabled.

It is supposed that LoRaNodes i=1..., for the computation of throughput. Where N generates every τ_i seconds a packet which occupies the channel for t_p,i in order to be transmitted. The duty cycle limitation for this simulation section is always 1% and when not specified, it is not applied at all. The main aim is to test the LoRaWAN access scheme. The network offered traffic is computed as described in the equation below(Mhaidi et al., n.d.):

$$\sum_{i=1}^{\mathrm{N}} \frac{t_{p,i}}{\tau_i} \tag{6.2}$$

The fraction of LoRa nodes packet transmission over time taken by the LoRa channel is called offered traffic as expressed in equation . It is important to note that, the LoRa channel is underutilised if $G<1$ where no packet transmission or communication between the devices takes place in the network. However, if $G>1$, it simple states that even during a free flowing transmission in the network some packets will attempt to use the same channel simultaneous, which may lead to packet collision. Therefore, throughput S is obtained through a given value of G as follows:

$$S=G\cdot P_{succ} \tag{6.3}$$

Again, the total number of packets sent and total number of packets successfully received ratio in the simulation is said to be the approximate packet success probability denoted as P_{succ}. Perfect synchronization between LoRa devices inspired by a network offering of 1 can prevent the high packet loss during transmission by mitigating the probability of packet collision, and that will result in throughput of 1. Of course, it is very difficult or impossible to achieve a 100 percent free flowing synchronisation between the LoRa devices, so $S<1$ is expected.

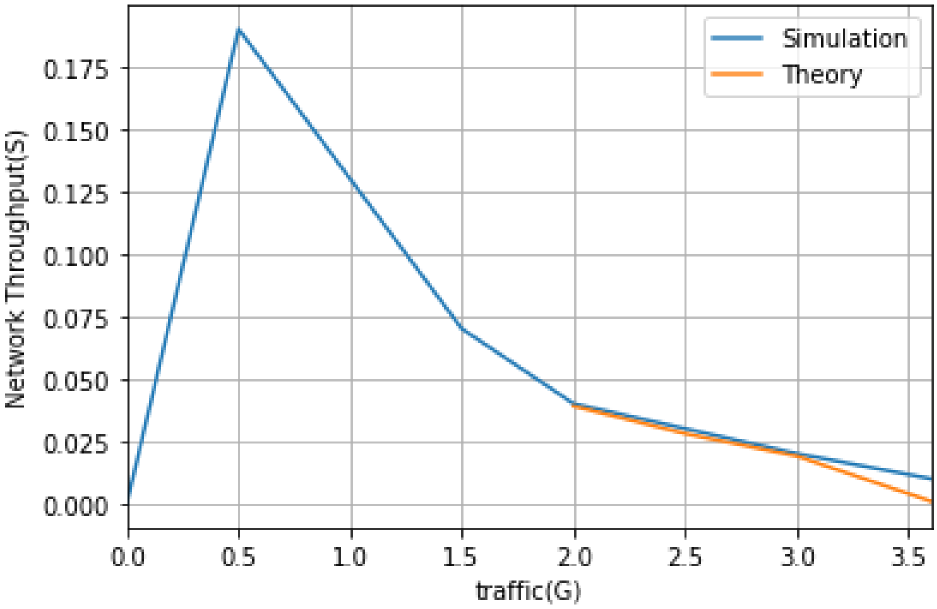

Figure 6.14: Ideal packet collision and throughput of SF=7.

It is expected that a shape of the throughput becomes curved under ideal channel condition, and followed typically ALOHA network in a varying offered traffic G as shown in Figure 6.14 All LoRa nodes are configured to transmit using SF7 and all transmitted packet have the same time-on-air (ToA) provided payload length is fixed and Gateway receives the packets at the same rate of power. These conditions take place when the link measurement model is off. The number of LoRa nodes N plays a significant role in expressing the traffic offered by the network as shown below:

$$G=\frac{N\cdot t_7}{\tau_i} \tag{6.4}$$

This transmission happens at a fixed payload length for all packets using SF7 as a range of transmission, where t_7 is ToA. This equation is very influential in the performance results as shown in Figure 5.8. The exact expression exist for throughput trend typical ALOHA such that:

$$S=G\cdot e^{-2G} \tag{6.5}$$

After this validation, the impact of using the varied real wireless channel and SFs is evaluated. The proposed link measurement model of the long-range component is used. It is observed that the continuous LoRa devices communication with the GW is highly influenced by the presence of real wireless channel by allowing the usage of all possible SFs. By using different SFs, the network achieves the quasi-orthogonality of transmission because the packets can chose different transmission range.

Another study that was conducted for the throughput matrix included a highest SF 12 transmission to evaluate the impact on performance of LoRa networks, especially with unwanted signals. For that evaluation, a network simulation was created and LoRa devices that needed to transmit through SF 12 were configured to never transmit any packet in the process of simulation. However, the total generated traffic still included traffic of those devices. Generally, it is a norm to find generated packets unable to transmit and still contribute to the lost packets in the ratio of P_{succ}, except transmissions in the network these packets generate no interference. The Figure 6.15 demonstrates the simulation results of the performed throughput experiments. When the system load is high LoRa device present in the network benefits from excluding that with the highest SF since the collision with other LoRa device transmission is reduced. Therefore, this increases the success probability almost up to $S_{gain} = 0.12$ as compared to the scenario where the packets that transmit with SF 12 are included.

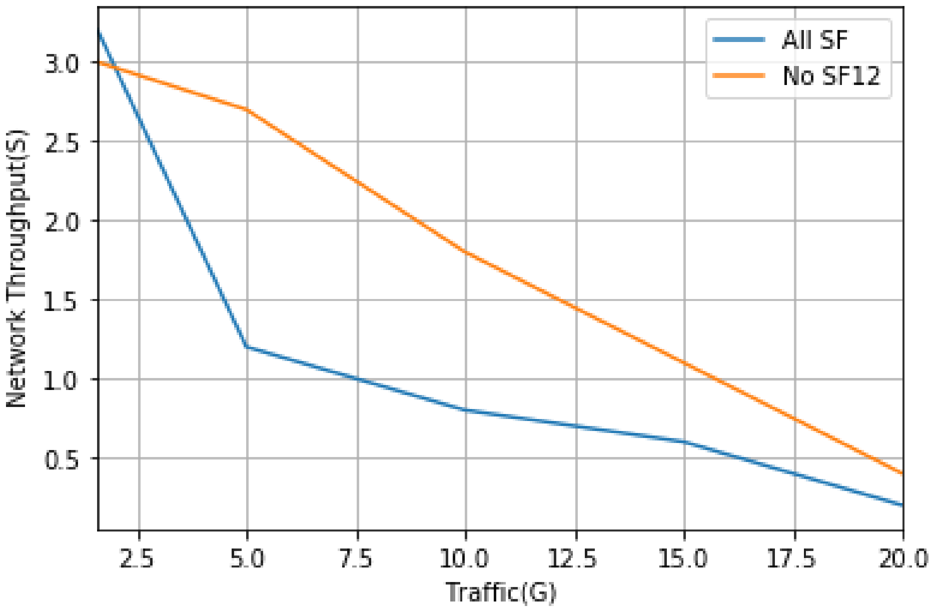

Figure 6.15: Throughput comparison with and without SF = 12.

Furthermore, the throughput of the network is negatively impacted due to the low offered traffic and by the lack of transmission by some of the packets causing almost $S_{loss} = 0.1$ loss. This is mandatory by the LoRa alliance standard which excludes the LoRa nodes that uses SF12 to transmit from the public network. These devices stand a very good chance of having a good success probability should they be given better sensitivity of the GW to SF12.

In discussing our findings in terms of network throughput, we compared the performance of our improved algorithm with the study that was done in (L'ecuyer et al., 2002). In both studies the evaluation of networks with all SFs and network with only SF12 were demonstrated.

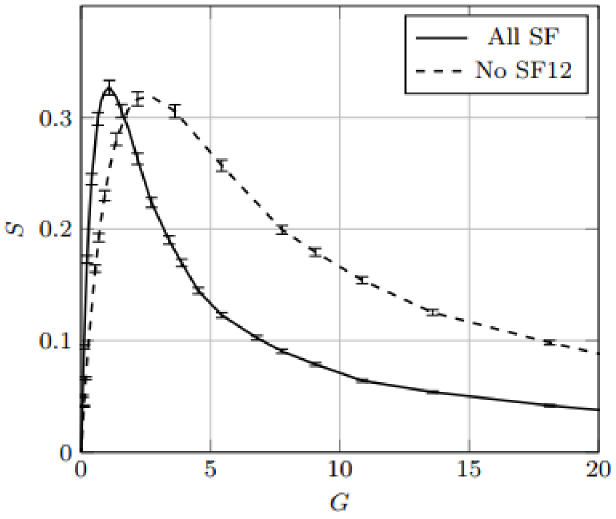

Figure 6.16: Network throughput with and without SF12. L'ecuyer et al. (2002).

Their simulation results are shown in Figure 6.16. It is a known fact that when a system load is high, it is beneficial to exclude LoRa devices with a high SF due to a reduced collision with other LoRa devices present in the network. The algorithm improved and implemented for our study gave a slight success probability improvement of 0.1% when compared to the study which has $S_{gain} = 0.12$. This depends on the SF employed by a LoRa node since lower SFs use the channel a bit less as compared to higher SFs and the traffic is computed based on the same transmission period for all end devices.

Finally, we discuss the decision of 1% duty cycle. When the duty life cycle is at 1%, it limits the traffic in the network which in turn reduces the collision. This is beneficial for the system as more packets will reach the destination and improve the throughput after experiencing the decrease in performance up until all LoRa nodes in the network are under effective duty cycle limitation as shown in Figure 6.17. This allowed the network throughput to stabilise at $S_{1\%} = 0.14$ as a fixed value. The increase of the offered traffic would follow after the stabilisation counters the continuous drop in performance provided the no limitations were applied and can ensure a gain in performance for a very small additional complexity in the ED software.

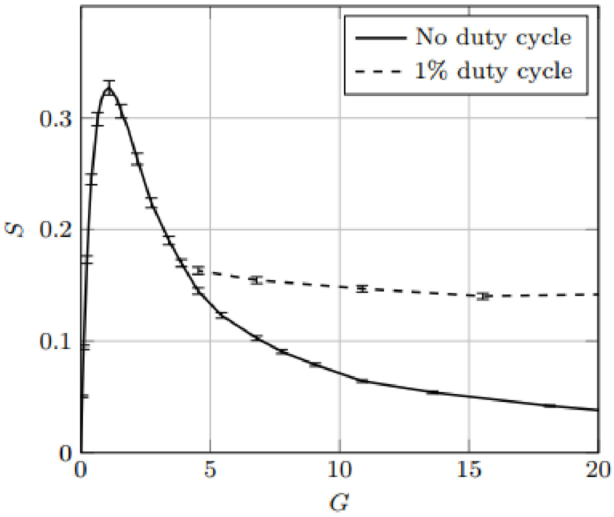

Figure 6.17: Network throughput with and without SF12. L'ecuyer et al. (2002).

6.6.2 Success Probability Performance

The aim of this simulation experiment is the estimation probability of successfully receiving a transmitted packet from LoRa nodes to LoRa Gateway(s). Since the interest of this simulation is to evaluate the real network performance, the network scenarios varied the number of Gateways from one to two. The Gateways were randomly and centrally distributed by implementing an enhanced algorithm. In the simulation tool, the radius covered by the GWs were specified for precise results. Even though some network simulation scenarios featured more than one GW only LoRa devices within the range covered were considered. Therefore, it was only LoRa nodes within the radius that had their generated traffic considered for success probability (Mnguni, Mudali, Sibeko and Adigun, 2019).

This experiment was mainly focused on the successful packets arriving at the GW as the function of the number of LoRa nodes present within the covered area. Figure 6.18 shows the decline of the probability success ratio as the network expands. All packets that arrived at the GW under the sensitivity were ignored due to shadowing or massive building loss. Therefore, this eventually led to a declining success probability because of path loss reception and interference of all different kinds. In this scenario, 22% of LoRa nodes were unable to reach the Gateway due to insufficient power.

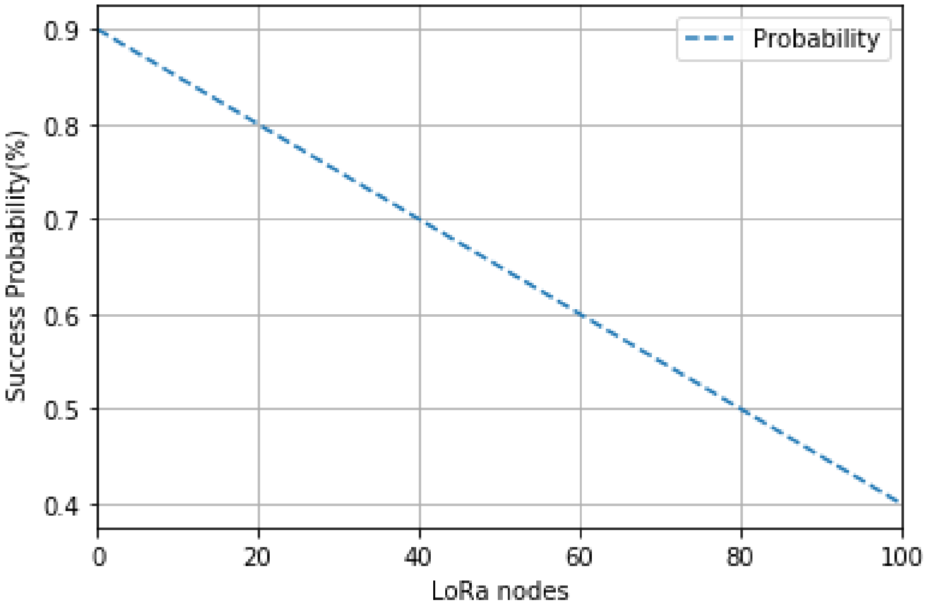

Figure 6.18: Packet success probability as a function of LoRa devices.

The simulation lasted one day with 5 hours of warm up and was repeated 10 times for accuracy purposes. As the network increased, the trend of the graph appeared to decrease linearly. The Gateway(s) that were tasked to accommodate all the LoRa devices from network scenarios were able to achieve a success probability of almost 91%. Aesthetically, Gateway are able to support around 10^4 nodes of the LoRa network according to Semtech(Kim et al., 2020), provided the probability success reached a fixed 95% of transmission.

6.7 Chapter Summary

The overall purpose of this chapter was to present the results and analysis obtained from several simulation experiments conducted for the LoRaWAN networks. Furthermore, this chapter gave an insight into the nature of data collected during simulation experiments as well as the technical issues experienced during the process. For every subsection, certain experiments were conducted with the aim of evaluating some LoRa network metrics such as impact of SFs, energy consumption, PDR, throughput, success probability etc. The results and analysis of each experiment followed each presentation.

Section 6.4 examined the SF impact in different aspects of the study. The performance of SF under different LoRa networks when one network consists of a single Gateway and the other consists of two Gateways was to check whether the network needed many GWs deployed for free-flowing connection or accurate positioning of those GWs. In that section, it was observed that SF7 has the highest average usage of transmission SFs with close to 25 LoRa devices using that SF. This reveals that a lot of devices were not far away from the Gateway(s) during the simulation. In the same section, we also evaluated the energy consumption for the two network scenarios with respect to the SFs where the scenario with one Gateway consumed more energy than the other scenario with two GWs.

We also evaluated payload very closely against the energy consumption and time-on-air where the aim was to see the packet in transmission and evaluate the delays. In section 6.5, after the experiments were conducted, a PDR equation was used with the aim of evaluating the relationship between the LoRa nodes deployed for the network scenarios and PDR for the packet transmitted. The simulation results obtained over 60% of delivery ratio which was more average than of the upper and lower links provided by a simulation tool. Finally, in Section 6.6, network throughput and packet success probability were all considered for different purposes. We wanted to evaluate the improved algorithm as to see how it will perform in the network throughput.

In this chapter, we also discussed the experimental work carried out with a FLoRa simulator against other existing work to achieve the five (5) objectives set out for this study. The objectives were:

- To establish the state-of-art Gateway placement and identify existing algorithms for computing the candidate locations for Gateways to be placed and have the optimal location selected from them

- To compute the maximum coverage of the network through ADR and SF in LPWAN.
- To determine the best possible position in which Gateways can be placed for a long-range technology in LPWAN when using the LoRaWAN algorithm.
- To design and implement the new algorithm in LoRa networks.
- To test the newly implemented algorithm in LPWAN environment using LoRa technology.

To achieve these objectives performance metrics were required. The SF was determined as the best performance metric as this could accurately evaluate the LoRa network in transit, since the primary goal LPWAN is transmitted at a low power. Additionally, an algorithm was improved and implemented in the FLoRa simulator and thereafter a set of experiments were executed in which different aspects of the LoRa network performance were examined. The impact of the improved algorithm was examined through the comparison of SFs at different networks and distances. The average nodes were used for both scenarios created with different Gateways.

The most occupation of SF 7 tells us that most of the nodes in both scenarios were not far away from the Gateway(s). The other aspect explored in the study is energy consumption with different SF at different networks. However, there are also other metrics used to meet the objectives such as PDR, network throughput and success probability. In general, as shown in the literature review, the development of LPWANs requires the performance trade-offs and LoRaWAN is a no exception. Long-range nodes require not only large coverage ranges, but also high energy efficiency, as nodes may be placed in remote and difficult to access areas.

Chapter 7

Conclusion and Future work

7.1 Summary of work conducted

Internet of Things (IoT) is intended to bring every object in our surroundings into the internet and improve the quality of life of human beings. Hence, Gateway placement is vital to facilitating the communication in the process.

This work was set out to examine LoRaWAN, which is a new and promising LPWAN technology built for IoT devices. Specifically, this research focused on improving the Gateway algorithm for LoRa transmission in LPWAN and evaluate the performance of the algorithm through the simulation experiments conducted.

A Gateway placement algorithm for the newly designed technology LoRaWAN can be improved and implemented in various ways. Four research questions were developed and answered in the research. The questions are as follows:

- How can IoT Gateway placement algorithms for long-range transmission technologies enhance data rate in LPWAN?
- How do we maximise network coverage with the use of SFs and Data Rate in LPWAN Gateway placement?
- Which position is the best for locating Gateways for a long-range technology like LPWAN when using LoRaWAN?

To answer these questions, literature review was conducted, and the simulation tool was configured to consider a scenarios of 20 and 100 LoRa nodes with one and two gateway(s). A framework for LoRa simulation (FLoRa) was used due to its capability to simulate LoRa networks with large nodes. For a network with 20 nodes two experiments were conducted to vary the Gateways from one to two; likewise for the network consist of 100 nodes. After the introduction to the state-of-the-art Gateway placement, a LoRaWAN system and various models of different components were described with a special attention to LoRa framework with the description of its classes that were used to implement some of the models.

The experiments were conducted and SF was chosen as a primary matric to evaluate the performance of the improved algorithm in different Gateway placement in LoRa transmission. The experiments lasted for 1 day each with the warm-up period of 5 hours to make sure every node present in the network is able to send packets to the Gateway(s). To evaluate multiple options for experimental parameters, each experiment consisted of several tests. The results of the experiments for the performance were captured in different files with some captured from the terminal. Furthermore, SFs were not the only metric used. PDR was also calculated by an algorithm by examining the sequence numbers of packets sent by the nodes and packets received by the Gateway. Network throughput and success probability were also amongst the matrices used to evaluate the enhanced algorithm.

The conducted experiments were also intended to investigate the impact of ADR, waiting time, payload length, ACK, SFs, energy consumption and link checks. The summary of the findings and observations are concluded below.

7.1.1 Conclusions

The first research objective provided insight on the existing algorithms by establishing the state-of-the-art Gateway placement in different environments such as long-range transmission and short-range transmission. Furthermore, it also helped to explain in detail the background of LoRaWAN protocol, LoRa and LoRaWAN as the core fundamental of this study. After reviewing the existing algorithm, we saw the need to bridge the gap by improving the algorithm that helped to position Gateways to improve the network coverage and facilitate a flawless connectivity.

In the second objective, we dealt with the maximisation of the network coverage using of ADR and SFs in a LoRa transmission technology. After the algorithm was implemented in the simulation tool and ADR was enabled, the network scenarios were created with 20 nodes and the other with 100 nodes with a simulation period which lasted a day. It was observed that transmission of SFs could be increased by ADR-Node until the link budget allowed the LoRa nodes to transmit to the frame and to the server successfully. However, only SF can be increased by ADR-Node. TP remained the same in certain cases. A high SF and high TP were needed for a node to communicate with the gateways.

The results showed that SF7 is the most used transmission factor amongst the six. This means that both scenarios had nodes near the Gateway(s) with a slight improvement of 4% network throughput when the ADR was enabled from 80% to approximately 84% network coverage performance. This was also influenced by the algorithm implemented since the open source gave a very poor performance. However, the decrease of the SFs used was recorded due to distance and the time far nodes take to transmit packet to the Gateway. A decrease of energy consumption from the network with one Gateway to network with two Gateways was observed due to more channel options when the Gateways increased even though it is not cost effective. The difference in terms of energy consumption is approximately 0.21%. Energy per useful bit is also dependent on the SFs and payload, as the nodes continue to use big SFs the energy per useful bit increases. On the other hand, energy per useful bit decreases as the payload increases which all impacted by the distance and time. With the help of partial orthogonality between its SFs LoRaWAN access scheme provides a higher throughput with respect to a typical ALOHA-based scheme. Moreover, the reliability and coverage of the uplink is enhanced by an increase in the number of Gateways according to LoRaWAN architecture and approximately over 95% packet success rate is estimated with a realistic traffic model.

The next objective addressed the impact of algorithm in a LoRaWAN performance using network throughput and packet PDR. This was chosen based on the merit of performance since it has the potential to accurately measure the performance. PDR in upper link, down link and simulation experimental were calculated for performance purposes and the results showed that the algorithm used improved the PDR. The network obtained approximately 99.9% PDR when consisted of 10 LoRa nodes for both upper link and down link, with the 65% actual simulation obtained when the network consists of at least 40 LoRa nodes. However, even though PDR showed a significant improvement when enabling the ACKs, it is actually the results of low number of LoRa nodes in the ACK and simulator. This forced the transmission mode for the Gateway and in large networks was detrimental to the performance. Therefore, it was concluded that network size and the probability of gateways experiencing congestion play a vital role in improving PDR using the ACK. A high PDR can be achieved in a private network operating in a remote area with only a few nodes to turn on ACK while thousands of nodes might need to be supported by the public LoRaWAN network.

Further insight can be found in the results obtained using FLoRa simulator, where PDR, packet latency, varying SF, reporting time, and MAC payload size were all found. From the results, we concluded that smart grid application LoRaWAN can be used if they use small packet sizes (in the order of ten of bytes) and work with low reporting time (in the order of minutes). Given that kind of configuration, a range 0.9% to 0.95% of PDR can be expected. However, with the help of our improved algorithm, we recorded almost 98% of PDR at the payload size of 10 Byte since payload was varied from 10 to 100 Byte. Compared to many studies, this was a massive network performance improvement provided 90% of PDR were achieved when the payload size was kept under 45 Byte with a BW of 125 KHz and a CR of 4/5. It was observed that with the increase of reporting time, the delivery ratio also increased since there is less traffic in the channels hence collision of packets was mitigated and success rate was improved.

7.2 Future Work

For future development, the simulator need to be improved and extended with the intention of allowing further analysis and aspect of the LoRa network. An improved simulator will be of help to simulate different strategies to perform a bootstrap of the network, to evaluate the effectiveness of different ADR schemes, frequency planning and the co-existence of other networks working in the unlicensed spectrum, to investigate the Direct Link (DL) transmission impact on the system and finally further investigate the optimal Gateway placement in the LoRa networks. Another possible future improvement of this study is the modeling of FLoRa and its communication links with Gateways which will allow the evaluation of different system management strategies and identification of bottlenecks.

In future we also intend to build a testbed with the aim of bringing the technology closer to the market of Internet of Things and further improve the quality of life. The latest version (v3.1) will be added to the LoRaWAN protocol as it is an active development. This version adds up several security changes and supports handover during roaming. The updates of mDot library and Gateway are released by Multitech regularly. These new features and changes can all be evaluated using the developed testbed. The testbed will be a suitable platform to evaluate the LoRa PHY layer since this study focuses on evaluating the LoRaWAN performance.

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