A comprehensive analysis of LoRa/LoRaWAN effectiveness using WaterGrid-Sense in a real system deployment

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Dissertation submitted in fulfilment of the requirements for the degree *Master of Science in Computer Science* at the North West University

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Declaration

I, **Oratile Clement Khutsoane** hereby declare that this research project titled *"***A comprehensive analysis of LoRa/LoRaWAN effectiveness using WaterGrid-Sense in a real system deployment**" is my own work carried out at North West University, Mafikeng Campus and has not been submitted in any form for the award of a degree to any other university or institution of tertiary education or published earlier. All the material used as source of information has been duly acknowledged in the text and referenced.

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Dedication

I dedicate this research dissertation to my late mother:

Ms. Goitsemodimo Mosweu,

And my late Great-Grandmother:

Ms. Mmamolete Maria Khutsoane,

Thank you for raising me and taking care of me when I was young. Without you, I would not be where I am today.

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Firstly, I would like to thank almighty God for directing my steps until this day. He said to me "I am always with you, everyday till the end of time" Matthew 28:20. I would also like to thank myself for always pushing through the odds, without believing in myself I would not be where I am. The Lord said "Let no one despise your youth, but be an example to the believers in word, in conduct, in love, in spirit, in faith, in purity." 1 Timothy 4:12 in this verse I find perseverance, not forgetting my motto "Never Stop Learning" which makes me an inquisitive person and to always want to learn chase knowledge and wisdom.

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Abstract

LoRa also known as Long Range is a leading Low Powered Wide Area Network because it operates in unlicensed bands and has attracted widespread research. However, to continually improve this technology and for it to remain attractive, identification of gaps and future directions for LoRa network deployments via comprehensive analysis and evaluations are essential. This is critical to improving its performance in real-deployments in order to realize it for Machine to Machine communications. Existing works lack thorough investigation of LoRa as a new promising technology for Internet of Things deployments. Therefore, this work carried out an investigation of LoRa effectiveness for real world deployments. The constructive research design is employed, which composes of both qualitative and quantitative research methodology. We conducted this study on an operating smart water management system that uses LoRa for its communication among network nodes and on a network environment characterized as harsh. The network employed 34 nodes and the data from the nodes was collected for almost a year and was used to discover insights that could not be possible with short time experiments using fewer nodes or simulation works investigating LoRa. To visualize the data from the nodes and do interpretations, a web based dashboard data visualization tool was developed. The results of data collected and visualized using the developed tool revealed that LoRa was effective and reliable at the initial stage but as time goes on, the network started experiencing difficulties, which in turn affected the reliability of the network and potentially its effectiveness. The findings indicate that although Low Powered Wide Area Network aimed to alleviate network maintenance and costs, overtime this network's demands could be costly. Moreover, large number of nodes start to disconnect from the network due to their nature of link profiles and the harsh environments caused the LoRa adaptive data rates to start using link-demanding parameters, which consequently exhausted the battery life of the devices. The obstacles involved between the links play a bigger role in attenuating the performance of the network. The battery is charged through solar energy as an external energy harvester and we noted that the nodes charged through a solar source should be exposed to sunlight otherwise they end up in a reset state, where they are sometimes offline from the network. Improvements to this network rest on improving the LoRa adaptive data rate to be fair in allocating the network resources for communication. The powering of the network nodes also needs attention to prove that LoRa nodes can last for at least a decade without the need for battery change. Moreover, the visualization tool developed is not limited to this work. This work was successfully carried out and future works were identified.

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List of Acronyms

ADC: Analog to Digital Converter

ADR: Adaptive Data Rates

AP: Application Server

BS: Base Station

BW: Bandwidth

CSS: Chirp-spread-spectrum

CDMA: Code Division Multiple Access

DVT: Data Visualization Tool

ED: End Device

FEC: Forward Error Correction

FSK: Frequency Shift Key

GLSD: Geo-Location Spectrum Database

GW: Gateway

IIoT: Industrial Internet of Things

IoT: Internet of Things

IWSN: Industrial Wireless Sensor Networks

JSON: JavaScript Object Notation

LAN: Local Area Network

LNS: LoRa Network Server

LOS: Line of Sight

LPWAN: Low Power Wide Area Network

LRC: Long Range Communication

LTN: Low Throughput Network

M2M: Machine to Machine

MCU: Microcontroller Unit

NLOS: Non Line of Sight

NS: Network Server

P2P: Point to Point

PDR: Packet Delivery Ratio

PER: Packet Error Rate

QoS: Quality of Service

RSSI: Received Signal Strength Indicator

Rx: Receiver

Tx: Transmission

SF: Spreading Factor

SNR: Signal to Noise Ratio

SoC: System on Chip

SWMS: Smart Water Management System

TOA: Time On Air

TVWS: TV White Spaces

UI: User Interface

UNB: Ultra Narrow Band

WAN: Wide Area Network

WDN: Water Distribution Networks

WSN: Wireless Sensor Networks

Definition of Concepts

End-device: refers to a network node in an IoT network.

Harsh Environment: An environment consisting of conditions that can distract the performance of a network.

Internet of Things: A system of virtual and physical devices equipped with electronics, software, sensors, actuators, and the ability to connect to the internet in order to collect and exchange information using standard communication protocols.

LoRa: A low powered wide area network, proving long range communication. Operating in unlicensed bands.

LoRaWAN: A LoRa communication Protocol.

Low Power Wide Area Network: A wide area network composed of low powered devices.

Mote: refers to an IoT sensor node.

Tranceiver: a device that is able to receive and send network signals.

Wireless Sensor Network: A network of sensor devices connected wirelessly.

CHAPTER 1
Introduction

1.1 Chapter Outline

This chapter introduces the study presented in this thesis. Background information is presented on the field of focus. A preliminary literature review was carried out to strengthen the proposed problem aimed to be attempted in this study. The relevant research questions and objectives for this study are described together with the methodology to be followed. The limitations and purpose of the study are also discussed. Lastly, the thesis organization is presented.

1.2 Introduction

Internet of Things (IoT) is a new promising paradigm that has presented itself as the next future of Internet. It is aimed at giving any object (i.e. thing) the ability to connect to the Internet and communicate with other objects ranging from cars, animals, plants etc. [1]. This contributes a lot to real world's problem-solving. IoT is an important feature on the future internet because it is expected in the coming near future to integrate various technologies by doing so enabling new applications that were not possible with the traditional paradigm of the Internet. Objects will be equipped with the intelligence to contribute support to intelligent decision-making without human intervention [2].

IoT has been applied in various environments to address and improve the quality of life and applications like smart transportation, industrial automation, and applications where human decision-making is complex, like natural and man-made tragedy where emergency response is needed. The objects in IoT are able to sense, locate, execute tasks, communicate with each other, and even communicate with humans. This is a remarkable development in the world of information communication technology as objects are realized to have basic senses. This allows them to be able to measure, to reason, and understand their surrounding environments and share this information among different platforms to create a common operating picture [3]. Though IoT has gained a lot of interest from researchers and developers, arriving at its vision comes with many challenges along the way. There are still open key challenges in terms of scalability, availability, interoperability, reliability, security, performance, management, spectrum etc., just to mention few [4], [2]. Moreover, recent literature surveys highlight these challenges, even though most researchers are trying to address them, there is a lot of research that needs to be done due to the broad nature of IoT.

Communication is the key point that brings all Things in IoT together to form an Internet of Things network [1]. Researchers have realized wireless communications over wired communication as an enabling technology and a perfect fit for IoT. This provides the benefits of mobility, cable-less, scalability, and easy connectivity of objects to the internet [5]. Moreover, Wireless Sensor Networks (WSN) is one of the most successful technologies used for IoT deployments [1].

WSN presents itself as a key part of IoT because it serves a purpose of enabling the interconnection and integration of the physical world objects with cyberspace. It also makes IoT developments and deployments inexpensive due to advances and innovation taking place in wireless communications. Its technology consists of low-powered wireless sensors that are valid as infrastructure for a deployment that will serve for a longer time [1]. Currently, WSN has been applied in different applications such as area monitoring, water monitoring, healthcare monitoring, environment sensing, leading to categories such as smart city, smart industry, smart energy, smart health etc. [6]–[10]. However, WSN is associated with many inherited challenges due to the sensor node constraints such as energy capacity, computational capability, and communication bandwidth [11], [12]. Network management and security still require more attention [13], [14], [1].

There are various applications with different requirements. For instance, different scenarios require different models of deployment with different parameters of a network. Smart transportation requires a network deployment that is able to handle high mobility, smart cities require network deployment that can handle long-range communications, and smart environment will require network deployment that can be able to handle natural disasters and so on. Today, several wireless communication technologies have been developed in each perspective ranging from short range (ZigBee, 6LowPAN [15], [16]) to the long, medium range (LoRa, Sigfox, UNB, weightless, LTE-M, RPMA, DASH7, THREAD, etc.) [17] [1].

Low Power Wide-Area Networks (LPWANs) will improve existing and many new IoT applications forming smart cities, due to the low power consumption and long-range communication associated with them. LPWANs operate in wireless bands that are licensed or unlicensed. The major characteristics of LPWANs that should guide the design for IoT networks are:

a) Low-cost devices for low-cost network deployment
b) Low power consumption
c) Easy to deploy network infrastructure nationwide
d) Secure
e) Extended coverage [1]

Moreover, many developments are ongoing in LPWAN's [18]. Nevertheless, one technology cannot solve all the challenges. Thus, LPWANs address only a portion of existing challenges in IoT. LPWANs are specifically targeting situations where extended coverage is most needed, with low cost of deployment, involving devices that are delay tolerant, do not need a high data rates and require low power consumption network [19], [1]. In particular, monitoring of a system or conditions is a perfect case where LPWANs fit [1]. LoRa is one of the LPWANs, it stands for Long Range (LoRa), it is a new industrial, scientific, and medical radio band (ISM band) wireless technology [20] best possible for eliminating repeaters, reduce device cost, increased battery lifetime on devices, improved network capacity and support large number of devices. It is a physical layer used for long-range communication (LRC) connection [1]. The main advantage of LoRa devices is their ability of LRC, low power consumption, scalability, a bi-directional communication link with adaptive data rates, single hop architecture, and star topology that contributes to energy conservation.

LoRa is a physical layer that enables an LRC link. It uses LoRaWAN, a wireless communication protocol developed by LoRa Alliance to serve for challenges faced with LRC for IoT. It caters for long range, low power consumption at a low bit rate due to its definition for a LoRaWAN based system architecture. This protocol and its network architecture have a great influence in determining a node battery lifetime, network capacity, quality of service (QoS), security, and a variety of applications served by the network [1]. Although some published work shows the effectiveness of LoRa, there is still a gap in terms of a comprehensive evaluation of this technology in a real deployment. Few papers present real deployment [15], [17], 21] with no focus on analysis and evaluation for LoRa. However, most evaluations performed on this technology and its devices have, up to now, been done through testbeds by researchers, [21], [22], [23], [24].

Therefore, this work will conduct a comprehensive analysis and evaluation for LoRa/LoRaWAN using a device named WaterGrid-Sense, developed by the CSIR for Water Distribution Network's (WDNs). It is a smart interface platform with the ability to monitor and control in real-time the components of a WDN. WaterGrid-Sense provides a great variety of usage and can be used in different applications. WaterGrid-Sense is in two-fold based communication technologies: short-range communication based on IEEE 802.15.4 that uses 2.4GHz and LRC based on LoRa using 868 MHz. The device is used specifically in a smart water management system (SWMS) for water usage metering. SWMS consists of three parts, smart water network, dynamic hydraulic model, and active network management. Currently, WaterGrid-Sense is attached to thirty four water meters and three pressure sensors. The collected data from the WaterGrid-Sense nodes is fed into the dynamic hydraulic model which consists of various techniques such as pressure management system [25], [26], leakage detection and localization algorithm [27], [28], [1].

1.3 Problem Statement

LPWANs are still not realized to their full potential [29], and therefore they are still in the evaluation phase,, within the research community with the objective of realizing their potential and effectiveness for new IoT deployments. To address the various existing challenges associated with LoRa/LoRaWAN a comprehensive analysis and evaluation is essential to highlight the existing gaps and recommend future directions for deployments. Recently there are some existing works where some evaluations have been carried out which can be classified into two groups; real implementation and testbed. In the first part, real implementation, LoRa-based devices have been used to implement real-time monitoring systems, such as works in [30] and [31]. Their focus was on the operation of the system and analysis of the collected data of interest. However, there is no comprehensive evaluation for LoRa/LoRaWAN that has been conducted in such systems. On the other hand, the evaluations conducted in most of the testbeds were limited because of the following:

1) A limited number of nodes are used, in some of them, it was just a gateway and a few nodes.
2) The experiments are conducted for a short period of time.
3) Most of them focus only on range (distance between node and gateway) aspect.
4) Most of them use single gateway and do not consider the influence of other networks or the interference involved.
5) Finally, these testbeds are not part of a real-time system.

Therefore, to highlight existing gaps and recommend future direction to address them, this work seeks to use a real-world deployed LoRa network to conduct a comprehensive analysis and evaluation for LoRa/LoRaWAN. A WaterGrid-Sense piloted by the CSIR was deployment on a real-time smart water management system that uses LoRa technology for its communication from sensors. The work focused on evaluation and analysis metrics that focus on most critical factors in LPWANs: communication range, low power, and robustness to environmental interference, network capacity, and network architecture. The network was deployed in a harsh environment where some nodes are behind buildings, hills, trees, etc. and different network conditions are deployed which might bring in interference. The nature of the network enabled us to consider many factors in our analysis, which allowed us to conduct a comprehensive analysis and evaluation.

1.4 Research Questions

Based on the results this work will further highlight the existing gaps and recommend future deployment directions for harsh environments. Therefore, in order to solve the above-stated problem we need to answer the following research questions (RQs):

RQ1: What are the evaluation metrics that forms part of the critical factors of LPWANs that should be investigated for LoRa/LoRaWAN?

RQ2: How can we measure, analyze, and evaluate the performances and effectiveness of LoRa/LoRaWAN?

RQ3: How can we identify the existing research gaps and future directions that could improve the performance of real deployed smart systems based on LoRa?

1.5 Research Aim and Objectives

1.5.1 Aim

The main aim of this research was to conduct a comprehensive network analysis and evaluation for LoRa/LoRaWAN on a real-world deployed network setup using WaterGrid-Sense a LoRa based device deployed on a smart water networks.

1.5.2 Objectives

To archive the main goal of this research, the following objectives shall be employed to answer the stated RQs:

RO1: Defining important network metrics for LoRa that forms part of the critical factors of LPWANs to further use on analysis and evaluation of LoRa/LoRaWAN.

RO2: To collect LoRa/LoRaWAN network communication data from the smart water management system and perform a comprehensive analysis and evaluation using relevant methods and tools.

RO3: To identifying research gaps and future directions that can improve the performance of real deployed smart system based on LoRa understanding and comprehensive analysis.

1.6 Research Methodology

When carrying out research, the selection of an appropriate methodology is of key importance. Selecting the correct methodology is essential to providing direction and transparency in terms of research reporting methods and techniques followed in order to responsibly show how data have been collected, prepared, analyzed, and discussed. In addition, the correct methodology and clear outline of the methods makes it possible for replication of studies if needed and ensures reliability of the results. In this research, the method of investigation that is more suitable to meet the stated goal is the constructive methodology, which consists of mixed strategies that are qualitative and quantitative in nature. This will be followed to gather the underlying base knowledge for our study and with the fair knowledge; we applied the proposed methods to achieve the goal.

Qualitative research approach is for exploring and seeking understanding of the underlying problem using theories. It is generally framed in texts. Quantitative research approach involves testing objective theories by studying the relationships between the given variables. These variables typically are in the form of numbers. Methods of analysis can be applied to both. Mixed methods involve mixing both the aforementioned approaches, collecting data for both research approaches. The assumption is that using mixed methods research provides a more comprehensive understanding of the research problem than using either [32].

In the subsections below, we discuss the research methods employed in this study to achieve the objectives and answer research questions highlighted earlier. Accordingly, we highlight that this study is conducted on an existing real world deployed LoRa network. The following approaches were employed and flow as shown in Figure 1.1. The main methods are explained below.

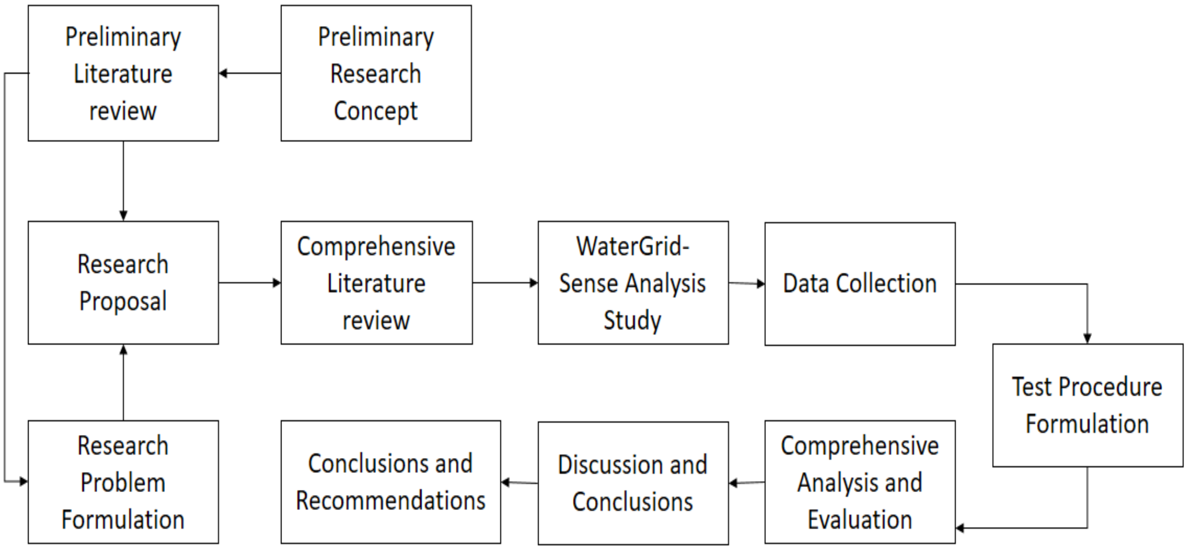

Figure 1.1: The Flow of the Proposed Research Work

A. Comprehensive Literature Review

A comprehensive literature review of previous works including the strategic methods and techniques related to this research in terms of IoT, wireless communication, low-power WAN, LoRa/LoRaWAN was carried out. This approach includes review and thorough analysis of the related literature; in preparation for analysis of WaterGrid-Sense commonly used devices for LoRa network are explored. The aim was to gain knowledge, which is valuable in this research.

B. Familiarize with WaterGrid-Sense and LoRa/LoRaWAN network aspects

A thorough understanding of WaterGrid-Sense, how it operates and its design, its network parameters and aspects. Literature in sensor node designs was explored. In addition, we get familiar with everything about LoRa and LoRaWAN.

C. Data Collection

Data collection involves accumulation, classification according to the defined variables, and storing of data, in most cases in an ordered manner. In the context of this research, this process enables us to analyze, evaluate, and predict behavior or make decisions from the insights gained along the process. A data collection interface was designed specifically for this work to pull all the data we need from the existing smart water management system. In this context, data is collected in the form of network packets in an equally timely manner from each deployed sensor node. The data was not pre-processed in any form; it was stored as raw as it is obtained. The duration of the data collection took close to a full year.

D. Test Procedure Formulation

Based on understanding and knowledge gained about WaterGrid-Sense and LoRa/LoRaWAN we formulated a test procedure and evaluation metrics based on WaterGrid-Sense and LoRa/LoRaWAN network aspects. Moreover, a data collection interface was designed specifically for this work to pull all the data we need from the smart water management system.

E. Analysis and Evaluation

Based on the defined test procedure and evaluation metrics we conducted a comprehensive analysis and evaluation of the collected data, and then based on the analysis and evaluations, some possible solutions for LoRa deployments enhancement were proposed as recommendations.

1.7 Relevance of Study

Developments on the realm of IoT are growing exponentially, as the IoT is promised to dominate the applications expected in the future. The concept of IoT is not new, however, like any other fairly new concept it started at a disadvantage and through research has seen many improvements. Mentioned earlier, IoT started using short-range technologies. Through research and developments, LPWANs has been discovered to serve as yet another improving concept to the IoT field. New technologies such as LoRa within the LPWANs have to be investigated, realized, and categorized for their best fit for the IoT applications. Therefore, this work seeks to explore the new LoRa technology through research approach. We aim to identifying the research gaps and suggest future research directions to assist researchers in improving the technology and realize its benefits.

1.8 Research Limitations

With this research study, we aim to contribute to the realization of LPWANs full potential as the capable and relevant communication technologies for mainly long range, low powered deployment solutions for the IoT. However, while this work acknowledges the existence of other LPWANs, we will only focus on LoRa as a leading LPWAN operating in unlicensed bands.

This research work used an existing network system to carry out the study. Therefore, we only utilized a single LoRa module from microchip called *Microchip RN2483*[33], it is a low-power, long-range transceiver used for LoRa communication. The comprehensive analysis and evaluations conducted in this study were based mainly on the impact of the physical environment factors, as stated in the problem statement the network is operating in a harsh environment. Other factors like external network interference, temperature, seasons etc. were not taken into consideration.

1.9 Research Outputs

Incorporated in this write-up is some work that has been done, presented, and published at an International Conference. This section describes the manuscripts as per publication status; the main authors are the Oratile, Isong, and Adnan.

I. **Chapter 2** is based on a paper entitled **"IoT devices and applications based on LoRa/LoRaWAN"** published in the proceedings of International Conference, *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, in* ***Beijing, China*** 29 October – 1 November 2017, published by IEEE. In this paper, we conducted a comprehensive review and analysis of the related literature.

II. **Authors:** Oratile, Isong, Adnan
Title: "WaterGrid-Sense - A full stack LoRa Node for Industrial WSN applications"
Submission: (To be submitted)
Journal Drafted from– (Chapter 3, 4, and 5)

1.10 Thesis Organization

This chapter (Chapter 1) gave an introduction and background, and gave an overview and general insights of the research work. In this chapter, a general description of a research plan was outlined which included a transparent presentation of the problem statement, research objectives, research goals, research methodology, and research limitations.

CHAPTER 2 present the literature review in the context of the technologies and concepts introduced in this chapter, which are the IoT, LPWANs and finally dwells more on LoRa and LoRaWAN as the main focus of this research. A comprehensive literature review was carried out and a comparative analysis of the literature is presented.

This work uses a sensor node called WaterGrid-Sense, sensor node designs on its own is a broad field. As part of objectives, an understanding of the WaterGrid-Sense, the node used in this study is essential. CHAPTER 3 presents the analysis of the WaterGrid-Sense and related works focusing on sensor node designs is explored and later a lab experiment was carried out, focusing on the node communication and power consumption.

CHAPTER 4 of this report presents the research design and methodology in detail. The proposed methods and tools to be used are explored and discussed in detail. CHAPTER 5, presents the implementation, results, and discussion of the data obtained during the period of study. In conclusion, of the thesis, CHAPTER 6 will present the summary of the work, reached conclusions, and finally proposed future works.

CHAPTER 2

Literature Review

2.1 Chapter Outline

This chapter gives a comprehensive background study of IoT communication technologies. It will mainly focus on wireless communication technologies classified as low power wide area networks (LPWANs) commonly used in wireless sensor networks (WSN). We will start with the introduction, discussion on IoT and then present LPWANs with their comparisons. Moreover, we will also present LoRa and discuss the LoRaWAN protocol as well as present the related works in this regards.

2.2 Introduction

The Internet of Things (IoT) paradigm presents itself as the next future of the Internet. It is aiming at giving any object (i.e. thing) the ability to connect to the Internet and communicate with other objects ranging from cars, animals, plants etc. Several types of research are being conducted on IoT, which led to its improvement and developing categories based on specific projects undertaken. For instance, formed categories that are commonly known are smart homes, smart cities, smart transportation, smart environment, smart grid, and smart water systems [34]–[36]. There is no fixed model of deployment for IoT but all depend on use cases. One solution of IoT-based in one category can serve as a solution in another category. This has led to experts anticipating the connection of more than 50 billion objects by 2020 [37].

Communication is the key point that brings all things in IoT together to form an Internet of Things network. Researchers have realized wireless communications over wired communication as an enabling technology and a perfect fit for IoT. This provides the benefits of mobility, cable-less, easy to add more devices to the network, and easy to give any object the ability to connect to the internet [5]. Moreover, WSN is one of the most successful technologies used for IoT deployments. WSN presents itself as a key part of IoT because it serves a purpose of enabling the interconnection and integration of the physical world objects with cyberspace. It also makes IoT developments and deployments inexpensive due to advances and innovation taking place in wireless communications. Its technology consists of low-powered wireless sensors that are valid as infrastructure for a deployment that will serve for a longer time. However, WSN is associated with many inherited challenges due to the sensor node’s constraints such as energy capacity, computational capability, and communication bandwidth [11], [12]. Network management and security still require more attention [1], [13], [14], [38]–[40].

Different scenarios require a different model of deployment with different parameters of a network. For instance, smart transportation will require a network deployment that is able to handle mobility, smart cities will require network deployment that will be able to handle long-range communications, and smart environment will require network deployment that will be able to handle natural disasters and so on. Today, several wireless communication technologies have been developed, in each perspective, ranging from short range (ZigBee, 6LowPAN [15], [16]) to long, and medium range (LoRa, Sigfox, UNB, weightless, LTE-M, RPMA, DASH7, THREAD, etc.) [17]. These existing and many new IoT applications are envisioned to be improved by LPWANs due to the low power and long-range communication associated with it. LPWANs operate in wireless bands that are licensed and unlicensed. The major characteristics of LPWANs that should guide the design for IoT networks are:

- Low-cost devices for low-cost network deployment
- Low power consumption
- Easy to deploy network infrastructure nationwide
- Secure
- Extended coverage [1]

Currently, there is a lot of development in LPWAN networks [18]. However, one technology cannot solve all challenges. Thus, LPWANs are deployed to address only a portion of challenges in IoT. LPWANs are specifically targeting situations where extended coverage is most needed, with low cost of deployment involving devices that are delay tolerant, those that do not need high data rates and require low power consumption network [19]. In particular, monitoring of a system or conditions is a perfect case where LPWANs can be used. In this case, we assume LPWANs can be a perfect fit for Water Distribution Networks (WDN) where little data is collected in order to monitor different parts of the network. This chapter also performs a comprehensive survey of LoRa devices and their behaviour in different applications to see their potential viability to fit on water distribution network for monitoring purposes [1].

2.3 LPWANs

Existing and a lot of new IoT applications are proposed to be improved by LPWAN's because of the role they play in low power long-range communication. Applications including and not limited to grid systems, automotive, metering, and monitoring, requiring long range communication will be catered by this new technologies. LPWANs operate in wireless bands that are licensed and unlicensed. Key characteristics for LPWANs that should guide the design for IoT networks are:

Low-cost devices for low-cost network deployment: a typical IoT project solving a critical problem can require a number of devices to operate. Therefore, low-cost IoT infrastructure is key to enabling effective problem-solving in this era. Low priced devices enable testbeds to be designed and experiments to be carried out. This kind of need enables easy deployment and maintenance of a network. Software and hardware have to be simple and straightforward to minimise the complexity of such networks.

Low power consumption: extensive battery consumption should be avoided; the use of simple protocols that do not need extensive routing should be used e.g. ALOHA. The devices should be able to operate for a long time without the need for a battery change, and no battery and or no sim card devices are preferred [14]. This also contributes to the minimal maintenance of such networks thus reducing costs. The encouraged topology to be used is the star topology; synchronization and using mesh topology should be avoided, the devices should operate only when there is a need.

Easy to deploy network infrastructure nationwide: LPWANs are aimed to address long-range communication, this means devices should communicate at a distance of more than few km's. One of the reasons why the LPWAN uses ALOHA is to simplify the deployment process, this kind of network makes it easy for an additional node to be added to the network thus enabling the network scalability.

Security: data transmission between the links should be secure. The network should not allow intruders to have access to the meaningful data. RF link should be resistant to jamming [41].

Extended coverage: for an application that requires deep indoor deployments LPWAN is expected to provide coverage, by enhancing the link budget up to 15-20 dB for such applications as pipe leakage monitoring, and underwater sensor deployment networks which needs extended coverage.

Currently available LPWANs are designed to the above specifications, notable at the moment are, LoRa by Lora Alliance, Sigfox, UNB, weightless, LTE-M, RPMA, DASH7, THREAD, etc. these LPWANs technologies are able to achieve long-range communication with low power consumption, at a low rate and high latency in a reasonable amount of time [42].

2.3.1 Popular LPWAN Communication Technologies

In this subsection, we discuss and briefly present the common LPWAN communication technologies. We will discuss how they work, and the technologies they incorporate. Finally, we will provide a comparison showing their strengths and weakness.

SigFox: offers a full ecosystem as a package, including all the necessary components to operate an LPWAN network, network infrastructure, network controllers, servers, and UI's [41]. Sigfox is a cellular-like based technology, which offers connectivity to remote devices via Ultra Narrow Band (UBN) technology. It fits for low data rate applications and requires fewer antennas, unlike the traditional cellular networks. By using their patented UNB, Sigfox achieves efficient use of bandwidth which results in low noise levels resulting in a high sensitivity of the link, and ultra-low power consumption by the end devices [43]. Sigfox has already deployed thousands of devices in different countries. Sigfox uses a low throughput network (LTN) architecture, which consists of nine interfaces:

1) The radio access communication between the end devices and the gateways.
2) Communication between gateways and servers through the WAN medium e.g. fibre, LAN, 3G.
3) Communication between LTN servers and application servers providers using IP protocol e.g. connection to the cloud.
4) The connection between LTN central registration authority and LTN servers
5) The connection between LTN servers, used when roaming.
6) The connection between LTN servers and OSS/BSS servers. Used for data exchange registration and status of the network.
7) Operations in the end-device between modules attached and data collection system.
8) The interface provided by service application providers for the user interface (UI)
9) The connection between the application provider and OSS/BSS servers.

The general overview on a network connection for Sigfox, is that end-devices are connected to the gateway in an ALOHA protocol, a star topology via radio frequency, the gateway connects to the internet or servers through LAN or another communication medium, the gateways can also connect to the Sigfox cloud. The message queue protocol used is MQTT between cloud and servers.

INGENU RPMA: RPMA (Random Phase Multiple Access) is an LPWAN technology proprietary to the company called INGENU, aiming at minimizing the cost of ownership. It provides high link capacity. RPMA prides itself with the ability to provide coverage and capacity. RPMA operates in the 2.4 GHz ISM band, unlike other wireless technologies that rely on the propagation properties of Sub-GHz so it has the advantage to leverage unstrict regulations on the spectrum throughout different locations [43]. The 2.4 GHz band does not have strict regulations thus it enables high throughput and more capacity. RPMA is a Direct Sequence Spread Spectrum, and a patented INGENU physical layer access scheme that is used for the RPMA uplink. The one-time slot can be shared by multiple transmitters, via Code Division Multiple Access (CDMA) offered by RPMA. Multiple demodulators are found at the receiver that deals with decoding signals that arrive at a different time within the slot. RPMA offers bi-directional communication between the link and end-devices, for downlink communication the link broadcast a signal to individual devices and start transmission. End devices reach for nearby base stations for transmission to reduce time-on-air and interference with other devices.

Weightless: Is divided into three open standards that can operate in unlicensed and licensed spectrums, proposed by WEIGHTLESS Special Interest Group. The standards are Weightless-W, Weightless-N, and Weightless-P whose key characteristics are range and low power consumption. Weightless-W supports several modulation schemes and a wide range of spreading factor. From 1 kbps to 10 Mbps transfer rate can be reached for packets of 10 bytes depending on the link budget. The uplink uses a narrow bandwidth at a lower power level to save the device's power [43]. This standard utilizes the TV white spaces and can cause problems if deployed in areas that do not have TV white spaces. Weightless-N and Weightless-P are globally available ISM band standards. Data rates between 2kbps-100kbps are offered by these two standards with the Sub-GHz bands at a 12.5 KHz for a single narrow channel.

DASH7: DASH7 is a full stack LPWAN that is proposed by DASH7 Alliance. It is an ISO/IEC 18000-7 standard. It employs narrow band modulation scheme utilizing two-level GFSK in Sub-GHz bands. It differs from other LPWANs in three properties: 1) its default topology is a tree topology but it can also use a start topology like other LPWANs. 2) The MAC protocol used by DASH7 forces end devices to check for an incoming downlink transmission on a regular basis. This gives the advantage of lower latency but with consequences of a slightly higher power consumption due to devices having to periodically wake up to check for incoming downlink transmissions. 3) DASH7 full stack network allows applications to communicate with end devices without going through complex latent protocols. However, it has the feature of forward error correction (FEC) and symmetric key cryptography.

Table 2.1: Comparison of LPWAN's

Metrics	LoRa	SigFox	Weightless	Dash7	INGENU RPMA
Modulation	CSS	UBN DBPSK(up), GFSK(down)	16-QAM, DBPSK, BPSK, QPSK, UNB, GMSK	GFSK	RPMA-DSSSS(up), CDMA(down)
Band	SUB-GHz ISM: EU (433MHz 868MHz), US (915MHz), Asia (430MHz)	SUB-GHz ISM: EU (868MHz), US(902MHz)	TV white spaces 470-790MHz, SUB-GHz ISM or licensed	SUB-GHz 433MHz, 868MHz, 915MHz	ISM SUB-GHZ & 2.4GHz
Data rate	0.3-37.5 kbps (LoRa), 50 kbps (FSK)	100bps(UL), 600bps(DL)	1kbps- 10Mbps	9.6,55.6,166.7 kbps	4.8kbps- 800kbps
Range	5 km(URBAN), 15 km(RURAL)	10km(URBAN), 50 km(RURAL)	5 km (URBAN)	0-5 km (URBAN)	15 km (URBAN)
MAC	Unslotted ALOHA	Unslotted ALOHA	TDMA/FDMA, Slotted ALOHA	CSMA/CA	CDMA-like
Topology	Star of stars	star	Star	tree, star	star, tree
Payload Length	up to 250B (depends on SF & region)	12B(UL), 8B(DL)	>10B, 20B	256B	10KB
Adaptive Data Rate	√	√	√	√	√
Security	√	No encryption	√	√	√
Indoor	√	√	√	√	√
Bi-directional	√	√	√	√	√
Battery Life	>10 Years	>10 Years	>10 Years	>10 Years	>10 Years

Above we described, discussed common LPWANs and Table 2.1 is used to show their characteristics with regard to LPWAN design goals. Area of controversy for LPWAN arises when a question of which is the best amongst them. To mitigate the controversy, using Table

2.1 it is clear how LPWANs are built for a common goal. LPWANs follow similar design goals and techniques [43], which allows them to provide long range communication with low power consumption. As can be seen in Table 2.1 there is a lot of common characteristics such as battery life, topology and usage of ADR. The differences and lies of different types of standards followed and modulations which in turns gives each LPWAN technology its uniqueness such as how far the communication reach and the maximum data rates that can be achieved this can also be seen in Table 2.1.

Different authors have ordered and classified different LPWAN's as leading, based on their adoption and convenience, mostly the argument is based on cost that comes with such networks. Authors in [44] listed Sigfox, LoRa and NB-IoT as leading LPWAN's, authors in [45] in their studies argues LoRa and IoT to be the leading LPWAN's and their studies is focused on this two technologies. Authors in [46] also mention Sigfox and LoRa as leading LPWAN's. From the above literature we can see that LoRa appears in all arguments. Additionally authors in [47]–[50]. The common reason for LoRa to be regarded as a leading LPWAN revolves around its operation on unlicensed bands, its robustness and sensitivity [44]–[50]. The below subsection focuses on LoRa and its protocol LoRaWAN.

2.4 LoRa

LoRa is a long-range low power wireless technology platform that uses unlicensed radio spectrum in the industrial, scientific, and medical radio band (ISM band) [20]. LoRa aims to eliminate repeaters, reduce device cost, increase battery life on devices, improve network capacity, and support a large number of device connectivity. It is a physical layer used for long-range communication. To achieve low power, most wireless technologies use frequency shift key (FSK) modulation. However, LoRa uses chirp-spread-spectrum (CSS) modulation to maintain low power characteristics for the benefit of increasing communication range. It is the first implementation for low-cost infrastructure to be commercialized using CSS. CSS has been used in long-range communications by military and space agencies due to its ability to withstand interference [1].

2.5 LoRaWAN

LoRa uses LoRaWAN protocol, a wireless communication protocol that has been developed by LoRa Alliance to serve for challenges faced with long-range communication within IoT. It specifically deals with long range, low power consumption at a low bit rate due to its

LoRaWAN-based system architecture. The protocol and its network architecture have a great influence in determining a node battery lifetime, network capacity, quality of service (QoS), security, and a variety of applications served by the network [1]. The following are the main characteristics of LoRaWAN:

Network architecture: The common architecture is a star topology following ALOHA protocol. The sensor nodes communicate directly with the gateway, which transfers the data to the network servers.

Network capacity: The gateway used by LoRaWAN network should have a great capability and capacity to handle transmissions from a massive volume of nodes. LoRaWAN achieves high network capacity by utilizing adaptive data rate and use of gateways equipped with multichannel multi-modem transceiver to simultaneously receive multi-messages on multiple channels.

Network lifetime: The nature of LoRa contributes towards the long lasting of nodes batteries. Nodes do not transmit at all times rather they transmit on schedule or when triggered.

Though LoRa signals still archive the best results while they are orthogonal, the gateway is able to accept multiple transmissions with different data rates on the same channel, this is because of data rate changes when the spreading factor changes. The scenario is when a link node is near the gateway there is no need for it to transmit data at a low rate and take a longer time whilst it is close, instead LoRa adjust the data rate to reduce the time taken transmitting. This concept is called adaptive data rate, and it contributes towards increasing the battery life of nodes. In order for the adaptive rate to be a success, downlink capacity should be sufficient. This makes more capacity for a LoRaWAN network and makes it scalable. When more capacity is needed, the network can be equipped with more gateways, increasing the data rates for the network. This feature makes LoRaWAN outstand because other LPWANs cannot scale the same way, due to their limits of downlink capacity.

LoRa devices are divided into three classifications, this means devices are created to serve their specific purposes and the creation of your LoRa device will depend on the application you intend to use the device for. LoRa based devices compared to other LPWAN devices are suitable for both deployments of indoor and outdoor spaces making it a suitable technology for smart cities, building applications, and home automation applications for low data rate applications [42]. Below are the LoRa Classes:

Class A (for all): Must be supported by all LoRa devices as it defines the default operation mode for LoRa networks. In this class, end-devices are always the ones initiating the transmissions, in a totally scheduled manner or signal triggered. The end-devices allow bi-directional communications whereby two receive windows are open for a fixed period to receive downlink messages immediately after an uplink transmission. If a server wants to send a downlink message it has to wait for an uplink from the end-device. End -devices operate at a scheduled time-based transmission and according to the need for communication. They use ALOHA protocol. Class A requires the least power from EDs even in cases that require bi-directional transmissions. Class A network is most suitable for monitoring applications where an ED action has to be triggered from the server [51]. Below are the characteristics of Class A:

1) Most energy efficient
2) Must be supported by all devices
3) Downlink available only after uplink Tx
4) Small payload and long intervals
5) Multicast messages
6) End-device initiates communication (uplink) [51].

Class B (Beacon): Class B end-devices operate on a bi-directional scheduled timeslot. However, before the end-device can open the receive window at the scheduled timeslot, a gateway sends a time-synchronized beacon. This allows the server to know when an end-device is listening. Therefore, Class B is suitable for applications that need a remote controller, e.g. actuators. Below are the characteristics of Class B:

i. Energy efficient with latency controlled downlink
ii. Scheduled communication synchronized with a beacon

Class C (Continuous listening): End-device receiving windows are always open; they only close when the device is transmitting. It is suitable for devices that are not bounded to energy, and devices that are connected to an energy source, hence receive windows are always open [52]. Below are the characteristics of Class C:

i. Devices which afford to listen continuously
ii. Downlink communication has no latency.

The LoRa developments are driven by an open, non-profit association of members collaborating to drive the success of LoRa and LoRaWAN protocol, with a mission to standardized Low Power Wide Area Networks.

Currently, expected developments are:

i. passive & handover roaming capabilities for LoRaWAN
ii. Class B clarifications
iii. Class A/C temporary switching

It is mandatory that an end-device to be able to communicate on the LoRaWAN network should be activated with the following information:

(DevAddr) Device Address:

i. 32-bit identifier
ii. Each end-device having its unique address within the network
iii. Each data frame should have the device address of the transmitting end-device
iv. The address is shared between the end-device and servers present within the network
v. This is mainly for network manageability and security enhancement

(NwkSKey) Network Session Key:

i. 128-bit AES encryption key
ii. Each encryption key is unique per device
iii. Shared between End-device and network server
iv. Very important for security purposes.

(AppSKey) Application Session Key:

i. Shares same characteristics with NwkKey, but provides application payload with security.

LoRaWAN currently has two activation methods:

Over-the-air Activation (OTAA): global key unique identifier and over the message handshake based, acknowledgment sent by the server for a device to join the network.

Activation by Personalization (ABP): shared keys constructed and stored at the initiation of the network. They are only kept for a specific network, a device that has all the requirements to operate on the network is activated at the production of the network and no additional steps are required.

2.6 IoT Devices and Applications based on LoRa/LoRaWAN

This section discusses several devices used for LoRa deployments together with their configurations and we briefly highlight which applications they were used for. A comparison of these devices used and applications will be provided in the next section [1].

a) *LoRaSIM* [53]

Bor *et al.* [53] investigated the scalability of a network composed of LoRa devices using LoRaWAN protocol. Their setup was based on a scalable network for a smart city application. To be able to study the link performance, they use NetBlocks XRange SX1272 LoRa module. They first studied the link performance of the device with practical experiments and they specified the limits to (i) communication range's independence of communication settings Spreading Factor (SF) and Bandwidth (BW) (ii) Capture effect of LoRa transmissions depending on transmission timings and power. The purpose of the studies was to assist them in the developments of models that will help them build a LoRa simulator, which they called LoRaSIM. According to the authors, the simulator captures link behavior and enables evaluation of scalable LoRa networks. They performed the smart city experiment on the LoRaSIM to avoid high cost associated with the real-world deployment of such networks. The results showed that a typical city would deploy at most 120 nodes per 3.8 ha. This is possible due to the typical ALOHA protocol. However, with dynamic multiple BS (gateways) the network would scale well [1].

b) *Troughs Water Level monitoring system* [31]

Tanumihardja et al, [31] designed a system to monitor troughs water levels using WSN that deploys LoRa and LoRaWAN as their physical layer and communication protocol. They designed a system for herdmen to monitor their trough ubiquity using their personal devices. The gateway used is a Raspberry Pi to push the sensed data to the server. The system is said to be self-configuring, as it is designed for cattlemen with a minimum background in engineering. They use LoRa operating at 915 MHz due to its availability in their location. ATMega is used for the deployed nodes around the farm to satisfy the low power system for remote areas while the float switch GE-1307 is used as the sensor to read water condition. In that study, bandwidth was measured as the distance between the gateway and the node which was adjusted due to how low the nodes were placed while the gateway was placed on top of the house that could be 8 meters high. They concluded that for this setup horizontal antenna polarization was suitable [1].

c) *Mobile LoRaWAN* [17]

Petäjäjärvi, *et al.* [17] conducted a research study to investigate the coverage of a LoRa network as distance increased between the transmitter (ED) and receiver (BS). The goal of their research was to find the maximum communication range the network setup could reach, based on the location of deployment. Their findings can be used in locations similar to theirs as LoRaWAN parameters are known to be different according to locations. They used the maximum spread factor (SF) which also improved the base station sensitivity. For the end-device LoRaMote was used and attached to both the mobile car and boat. The failed and successful packet transmission were measured as both the car and the boat were moving. The movement was increasing the distance between the transceiver and the Kerlink's base station (BS) that was placed at the top of the building at the University of Oulu at a height of 24 m. Their experiment focused on percentages of packets lost and transmitted. The frequency channels used were restricted to those of the EU regulations. However, the nodes were able to choose between the available six (6) channels for communication. Their results show 80% successful transmission for 5 km, 60% between 5-10 km and reasonable loss for distance more than 10 km for the node attached to the car. On the boat, 70% successful packets transmission for up to 15 km and communication range was reached for 30 km. From the results, they were able to present to attenuation model that can be used to estimate base station density [1].

d) *PHY and Data link testbed* [54]

Augustin *et al.*[54] designed a testbed to thoroughly evaluate the performance of the data link layer and the physical layer both via simulation and field tests. Their work is remarkable because they presented the in-depth analysis of the LoRa components. Similar to authors in [17], the study evaluated the LoRa network coverage among others by placing the gateway indoor and the end-device node in outdoor space. They varied the distance and the SF as they measured packet delivery ratio and their results show that better coverage and packets were achieved on the maximum SF, which is 12 than other lower SF. They concluded that a LoRaWAN network is able to achieve a higher delivery ratio [1].

e) LoRaWAN Single Node Throughput [54]

Authors in [54], also conducted a LoRaWAN experiment to evaluate the maximal throughput a single node can obtain, their test used six (6) channels of 125 KHz, and varied SF from 7-12. Several tests were conducted and in each test, 100 packets were transmitted with a maximum payload of 51 bytes. The results showed that for low packet sizes the channel duty cycle is not the one limiting the throughput but rather the period the end-device receive windows opens, the end-device cannot transmit packets if the receiver windows are still open. The authors concluded that the maximum size of the frame depends on the data rate used. Furthermore, LoRaWAN does not have a mechanism to split large payloads over multiple frames and that a transmission should never send a payload larger than 36 bytes. This is the largest payload for LoRaWAN resulting to loss of capacity if a large amount of data is sent. They also suggest that a fragmentation mechanism should be added in the next LoRaWAN specification revision [1].

f) LoRaWAN Nordic Cities [55]

Ahlers *et al.* [55], on their on-going research projects for measuring urban greenhouse gas emissions in Nordic cities, deployed a LoRaWAN - a low-cost automated system for greenhouse gas emissions monitoring network around their city. Their system addressed the issue of not having a system that gives statistics about gas emissions in Norway and making the data available to every citizen via municipality platform. They used two sensor technologies namely, Libelium's Plug & Sense Smart Environment Pro (PSSEP) and Sodaq's Autonomo (SA). LoRaWAN was the communication protocol used to cover their minimum gateways deployed across the city. In support of the battery life of nodes, they mounted solar panels beside their node for power support. Nodes were equipped with different sensors to measure different parameters of gasses. They were able to measure CO_2 levels for a period of six (6) months and the battery power remained constant throughout this period. From their research, they stated that this type of network setup that measures CO_2 does not exist. As an on-going study, they were able to see the viability of this type of network [1].

g) WaterGrid-Sense [36]

Abu-Mahfouz *et al.* [36] conducted a study on Water Distribution Network (WDN) and started a Smart Water Management System (SWMS) for water loss reduction. SWMS consists of three parts, smart water network, dynamic hydraulic model, and active network management. Initially, they developed a meter interface node [56], based on modulo sensor node [57] to collect water meter readings and send the information to the gateway [58]. They also developed a WaterGrid-Sense, which is a smart interface platform with the ability to monitor and control, in real-time, the components of a WDN. WaterGrid-Sense provides a great variety of usage and can be used in different applications. WaterGrid-Sense is in twofold based communication technologies: short-range communication based on IEEE 802.15.4 that uses 2.4 GHz and long-range communication based on LoRa using 868 MHz. WaterGrid-Sense has been piloted in the CSIR campus where it is attached to seventeen water meters and five pressure sensors. The collected data from the WaterGrid-Sense nodes is fed into the dynamic hydraulic model which consists of various techniques such as pressure management system [25], [26], [59] and leakage detection and localization algorithm [27], [28].

h) uPnP-WAN temperature monitor [60]

Ramachandran *et al.* [60] introduced uPnP-WAN device aimed at providing plug and play for none expects in embedded systems for IoT. The device is said to be able to achieve a range of 3.5 kilometres in ad-hoc suburban deployment. The main purpose of their work was to design a system to monitor the temperature of blood fridges in DR Congo. Their plug-and-play device battery is said to last 6 years in realistic real work operation. The geolocation of antenna elevation has an impact on the effectiveness of the range. The uPnP-WAN uses Microchip's RN2483 LoRa module for class A LoRaWAN operation. AtMega1284p micro-controller with 10 MHz MCU, 16 kB RAM, 128 kB Flash, is used to implement uPnP running Contiki OS with Erbium CoAP stack. The uPnP and RN2483 are interfaced by UART communication. Evaluations were made on battery life and range of the signal. The system proved to reach a range of 3.5 km because of the LoRA single-hop deployment architecture. Moreover, compared to their previously uPnP-WAN project that used mesh, the battery now from calculations is able to last 10 years. The uPnP-WAN was configured to transmit sensor reading to the gateway every 15 minutes and send a warning signal when the temperature sensed increases above 15 degrees Celsius [1].

i) LoRaWAN Channel Access [22]

Bankov *et al.* [22] studied the performance of LoRaWAN based on channel access as the most important component of machine type communication (MTC). The aim of their work was also to evaluate the weakness of LoRaWAN and proposed a solution. Evaluating LoRaWAN based on simulations does not provide full potential of such a system. Thus, their evaluation was based on a more realistic approach, that is, a real-world based project. The evaluations based on channel access showed that transmission collisions do occur when two transmissions at the same data rate overlap in time. Their network setup consists of N motes connected to a gateway. One channel is used for downlink and three (3) main channels for uplink. All channels are 125 KHz wide. The devices are set to use data rates from 0 – 5, which is SF of 7 – 12. All motes are set to transmit 64-bytes payload (51-byte being Frame Payload). They also studied packet rate error (PRE) and packet loss ratio (PLR) for load less (than) 0.1 per second. The network experienced small packet loss and when load increases more packet loss is experienced due to collisions that occur. With 100 motes, packets can be sent once per 20 minutes. The possible solution proposed is then to increase the density of LoRaWAN gateways [1].

j) LoRa FABIAN [61]

Petrić *et al.* [61] described their study and designed their LoRa based setup called FABIAN deployed in the city of Renne. Star topology following ALOHA protocol was used as the network topology. Evaluations were performed to measure QoS. The study focused on the traffic between the nodes and base stations. They were able to generate traffic similar to that (which) can be used in applications such as sensor monitoring. (They or the application) observed performance metrics such as packet error rate (PER), and RSSI related to LoRa Physical layer and signal noise ratio (SNR). The nodes used were composed of an Arduino and FroggyFactory LoRa Shield running a modified version of contiki OS. The end-device is configured to be able to communicate using the LoRaWAN protocol and Kerlink as the BS. The antenna was configured to operate in Bandwidth: 868.1-868.225 MHz, Channel size of 125 KHz, all SFs were used, coding rate 4/7 and transmitting power of 14dBm. They varied parameters that can affect QoS and results were presented [1].

k) LoRa Wi-Fi [21]

Kim *et al.* [21] designed a multi-interface module that integrates both Wi-Fi and LoRa to achieve low power, long range, and high data transmission. This was aimed to provide LoRa technology with the ability to transmit the high amount of data and offer different services with various sensors. The Elix board provided Wi-Fi and LoRa device composed of Semtech and Waspmote SX-1272 chipset, Raspberry Pi and Arduino. The Wi-Fi handler and LoRa handler sends data through Wi-Fi and LoRa module respectively. The system is integrated with a power and data scheduler that chooses between Wi-Fi and LoRa according to the priority of sensed data to regulate power usage. The experiments were much based on measuring the RSSI and SNR, from 6 km to a maximum of 20 Km communication range [1].

l) LoRa Indoor Propagation [24]

Gregora *et al.* [24] conducted a research experiment based on LoRa to test indoor signal propagation capabilities for LoRa technology - long-range coverage. Two scenarios were performed in which the receiver was placed in the basement of a building and on the top of the roof, with the transmitter position being altered as measurements are taken. The devices they used were custom made for the experiment. IMST iU880A was used as an end-device transmitter and it was connected to a PC by USB serial converter. The node setting is controlled from WiMOD LoRAWAN EndNode Studio. Power transmitter was set to 20 dBm (100 mW), data rate was set to 0, for SF 12, bandwidth to 125 kHz, and bit rate of 250 bps. WiMOD iC880A with SX1301 chip was the BS connected to Raspberry Pi, and it has an antenna with 4.5 dBi [1].

m) EM Energy Harvester [62]

Orfei *et al.* [62] conducted an interesting research in terms of battery-less LoRa wireless sensor network deployed in a real-world application to monitor the road condition of a bridge by measuring the temperature of the asphalt and the presence of rain. An electromagnetic vibration energy harvester based on (the) Halbach configuration powers the system. The energy from the harvester stored in supercapacitor (is used) to power the node. The critical component of the system is the ARM Cortex M0+, designed by Microelectronics. Attached to it are the temperature and water sensors. A LoRa module then transferred the data to the BS and the module used was the RN2483 by Microchip Technology. The MAC for this experiment is disabled for the LoRa module to keep power consumption low. Two antennas are used on the transmitter 433 MHz and 868 MHz. The factors used for LoRa transceiver were the payload of 8 bytes, the maximum power of 14 dBm, 868.1 MHz and SF 12. In addition, current and voltage measured with respect to time and energy harvested is 123 mJ. In conclusion, the system presented a battery-less wireless sensor [1].

n) LoRa Indoor Deployment [63]

Neumann *et al.* [63] conducted an indoor environment LoRaWAN experiment to evaluate its performance and observe its limitations and define its use in 5G networks. They showed that limitations were driven by the ISM band regulation, which affects the amount of data sent per day. In addition, if not set correctly at the initial configuration of the end-device data rate can also be a factor of loss. They deployed one gateway and one minimal server that decoded and logged the sent LoRaWAN frames to the database. The gateway was made up of a Raspberry Pi 2, Interfaced with IMST IC880A through an SPI bus. The packet forwarder code used was from Semtech and the end-device made up of Raspberry Pi 2 interfaced with LoRa mote RN2483 through UART interface. Parameters used were 3 default channels between EU 863-870MHz ISM band. Each channel bandwidth us 125 KHz and belongs to the same sub-band. The duty cycle of the sub-band was limited to 1%, and each channel used 0.33% [1].

Table 2.2: Comparison of Literature LoRa Applications

Device:	Nodes	Range	SF	Band	BW kHz	Payload (bytes)	TX Power (dBm)	Application	LoRa Module	Output
uPnP-WAN [60]	-	3.5km	12	868MHz	125	-	-	Monitoring System	Microchip RN2483	monitor temperature of blood fridges
Troughs Water Level monitoring system [31]	5	1 km 5km	12	915MHz	125	26	14	Troughs Water Level monitoring	Atmel HopeRF RFM95	The system utilized by cattlemen
Mobile LoRaWAN [17]	2	30km	-	868MHz	125	50	14	Testbed	Semtech SX1272,	attenuation model that can be used to estimate base station density
LoRaSIM [53]	2	100m	7-12	868MHz	125 250 500	20	2-17	Smart City (Simulation)	NetBlocks XRange SX1272	LoRa simulator that enables evaluation of scalable LoRa networks
Single Node Throughput [54]	1	2.8km	7-12	868MHz	125	51	14	Testbed	Semtech SX1276 MBED	evaluate the maximal throughput
LoRa Indoor Deployment [63]	9	60m	12	863-870 MHz	125	4	14	Indoor experiment	Microchip RN2483	LoRa limitations
EM Energy Harvester [62]	3	-	12	433MHz 868MHz	125	8	14	monitor road condition of a bridge	Microchip RN2483 by	Battery less LoRa wireless sensor.
LoRa Indoor Propagation [24]	1	-	12	433MHz 868MHz	125	-	20	Indoor testbed	IMST iU880A	Best placement of devices when deploying
LoRa FABIAN [22]	-	-	7-12	-	125	64	-	Testbed & Smart City	FroggyFactory LoRa Shield	Network Protocol Stack and experimental network setup (LoRa FABIAN)
WaterGrid-Sense [36]	15	1.25km	7-12	2.4GHz 868MHz	125	18	-	Smart water management system	Microchip RN2483	Smart Water Management System (SWMS)
LoRa Wi-Fi [21]	-	6 km 20km	12	-	125	-	-	Testbed	Waspmote SX-1272,	System that uses both WiFi and LoRa
LoRaWAN Channel Access [22]	-	-	7-12	-	125	64	-	Testbed	-	Increase gateway density to accommodate more motes in the network
PHY and Data link testbed [54]	-	2.8km	7-12	-	125	-	2	Testbed	Semtech SX1276 MBED	Higher Delivery Ratio
LoRaWAN Nordic Cities [55]	10	-	-	-	125	54	-	Testbed, Smart City	Libelium's plug & sense	municipal greenhouse gas monitoring

2.7 Comparative Analysis

Table 2.2 presents the parameters of different reviewed device settings based on their different LoRa and LoRaWAN applications. It should be noted that the above experiments approached their deployments differently; some used traditional single board computers (e.g. Raspberry Pi) attached with LoRa modules designed by different vendors which might behave differently accordingly and some used complete stack plug and sense devices. However, LoRa devices operate differently according to different regional regulations mainly in USA, Asia, and EU. Moreover, some are built specifically for specific regions. A LoRa device comes with default settings and can be adjusted based on the use case or experimental purposes. As shown in Table 2.2, it is clear that almost all the reviewed devices used the default 125 kHz bandwidth, which supports all SF 7-12. One important aspect or thing about bandwidth channel is that it does not change regardless of where the channel is located on the spectrum. In [53] they used three different BW 125 kHz as default, 250 kHz which is between DR3 and DR4, and lastly 500 kHz which was used for both upstream and downstream. Upstream it had 8 channels from 64-71 at DR4 while downstream also had 8 channels from 0-7 at DR10 to DR13. Moreover, most devices used transmission power of 14 dBm, with SF of 11 and 12 for good results. The transmission power of 20 dBm as used by [24] is considered good as it enables the system to mitigated noise interference and increases signal propagation. This transmission power is mostly used in 2.4 GHz ISM-band for relatively wide channels. The results show common parameter settings across the applications. However, a bit of exploration with different settings would enable a research to discover optimizations techniques for LoRa [1].

The range is at the core of LoRa devices and can be a short or long range. The shortest range observed in one of these studies was 50 cm in [63]. LoRa always gives near nodes first priority to reduce network congestion and near devices are able to transfer at a low TOA. Current research in LoRa technology is more focused on testing its ability and ensure long-range communication with low power consumption as the future innovations for IoT. The range is one of the critical factors of LoRa and in this case, most important as water meters for SWMS are in a distributed manner. In addition, satisfying results are observed in studies done by authors in [15], where they reached a link of 30 km between the gateway and the ED [1].

From the articles considered in this review, we found that different scenarios have employed to test the viability of LoRa technology such as the indoor deployment by [63] and [24] as well as outdoor deployment by [55] and [31]. Another important observed aspect is the flexibility of LoRa devices as they can be deployed in most network setups, its integration with other technologies and devices. For instance, Khan *et al.* [21] designed a system that combines LoRa with Wi-Fi to achieve maximum throughput together with long range. The most notable application was performed by Raza and Kulkarni [62] where they designed a LoRa device that is battery-less and harvests energy from the vibrations of the bridge as the cars pass by the bridge. Their solutions show that there are innovation opportunities with LoRa technology depending on the type of application carried out and the location of deployment [1].

Briefly, Table 2.2 shows the compared parameter settings of different LoRa devices and modules to see their differences as applied in different applications. It is visible that using a LoRa device in a network does not require a lot configuration, rather a configuration according to the setup needs. The future of LPWANs relies on the devices used, if these devices are able to meet the requirements and get equipped with functionalities that are more intelligent, they can create a broad future for IoT [1].

2.8 Discussion

With advances in IoT, devices that are able to communicate in a long-range space and consume less energy are a necessity. LPWAN has been formed or realized to serve this challenge. Currently, there are several innovative developments in LPWAN networks and technologies such as LoRa. In this literature, we surveyed IoT devices and applications based on LoRa/LoRaWAN, with the goal of discovering the current deployment of devices that are used in LoRa networks and the type of applications they are used for, in order to realize LoRa as an appropriate technology for future IoT deployments. From the literature analysis and evaluations performed, we summarized the results into a form of a table as shown in Table 2.2 for better understanding. We found that current works done on LoRa are similar and the devices used are standard across all the applications. Single board computers with LoRa modules attached were used in most deployments for LoRa communication. In addition, some applications used plug and sense devices, which are full-stack for LoRa deployment, but their shortfall is that they can be expensive for large-scale deployments. Moreover, the current deployments can be classified into two groups: real implementation and testbeds or simulations. However, the applications that dominate are those for monitoring purposes. Therefore the strength of LoRa lies in applications that requires less data rates, sending small amount of data, timed transmission, actuated transmission and less bandwidth. It is not suitable for communications that requires high data rates, real-time response or rather critical applications [44], [64], [45]. Moreover, we conclude by saying LoRa can be used in smart water management systems for sensing and actuation purposes which is the application utilized in this research work. However, to increase the adoption of LoRa in the future, there is a need to develop a generic monitoring and control platforms based on LoRa that can be used across different domains and various applications [1].

2.9 Chapter Summary

This chapter presented the background introduction of IoT and how LPWAN advanced its applications. We then introduced the concepts of LPWAN, we presented them and compared their different characteristics. LoRa technology was introduced together with LoRaWAN, their characteristics were presented. Moreover, after the background theory, we conducted a thorough literature study and review. A comparison of the literature was carried out to identify the gaps and directions. Lastly, conclusions were drawn from the study and contributed to the problem statement in CHAPTER 1.

CHAPTER 3
Analysis of WaterGrid-Sense

3.1 Chapter Outline

This chapter presents the study on WaterGrid-Sense, a sensor node piloted by the CSIR and used in smart water management system (SWMS) and equally used and explored as part of this work. Through literature, we discuss the concept of industrial wireless sensor networks (IWSN), its network characteristics and the design principles for IWSN nodes. Lastly, we present WaterGrid-Sense as an IWSN node and conduct a lab experiment to test energy consumption and communication behavior.

3.2 Introduction

IWSN consist of the autonomous large number of sensors distributed in a manner. Legacy industrial systems used wired networks, however, these networks were hard to maintain and expensive. WSN have invaded the industrial communication systems, and have positioned themselves as a driving force for industrial monitoring and tracking activities. Moreover, in order to be in line with the envisioned IWSN applications and take advantage provided by WSNs the research community has positioned itself in advancing the nature of WSN from sensor nodes designs, to communication technologies and protocols.

Surveying the current state-of-the-art in WSN, the advancements in the communication technologies, hardware design, software design, architecture, and efficient protocols design [65] for wireless sensor nodes has led to the emergence of a new range of applications that were not possible with wired systems or legacy WSN in IWSN and industrial IoT (IIoT). WSN are gradually replacing legacy wired systems due to their low-cost, rapid deployment, flexibility, ease of maintenance, scalability etc. [65]. WSN has evolved from short-range wireless communications for IoT to long-range wireless distributed networks (i.e. smart grids). Although WSN has received much interest and adoption from R&Ds, there still exist challenges in node designs, communications technologies, and protocols.

WSN consists of small resource constraint devices/nodes, hence such a network is limited in terms of memory, energy, and processing at the perception layer [65]. Therefore, most WSN does not allow sensor nodes to fully process the data rather their architecture is a three-layer stack, which allows sensor nodes to transmit the collected data to the gateway (GW) that relays that data to a network server that does processing of the data and makes intelligent decisions. The challenges that remain are (1) network communications technologies that are adaptive and do not consume extensive power from network nodes while transmitting data. (2) The design of intelligent low-cost sensor nodes that are resource efficient and resource aware. (3) Network topologies that are efficient, intelligent and fault tolerant. (4) Energy harvesting techniques to prolong sensor nodes' lifespan resulting in low maintenance costs.

When designing a sensor node, a one has to keep in mind the design principles and technical approaches that are categorized into three classes by authors in [65]: 1) hardware development, 2) software development, and 3) system architecture and protocol design. These principles are based on designing solutions for IWSN. In terms of hardware, a low-cost and low-power sensor is ideal as most IWSN consist of monitoring and tracking. Typically, a sensor node encompasses an onboard sensor interface, processor, transceiver, and power source interface/unit [65]. An energy harvesting source is a necessity in state-of-the-art node development. Authors in [66] explained the challenges based on node software and encouraged the use of various operating systems for nodes aimed at flexibility. They also designed a modular sensor network node optimized for research: it encompasses the use of a dual boot between TinyOS and ContikiOS for flexibility and operability. Recent developments in wireless communication links have given birth to low-powered networks classified as low power wide area networks (LPWANs), enabling wide area communication for low powered devices, traditionally, wide area links required a high amount of power.

In this chapter, we describe WaterGrid-Sense a sensor node for pressure and pulse sensing. WaterGrid-Sense is a smart interface platform with the ability to monitor and control in real-time the components of a network. The node is based on the literature study of CHAPTER 2 on LoRa/LoRaWAN based devices, the findings are that at present there are no full-stack LoRa nodes available. Moreover, R&Ds have been using either single board computers and attaching a LoRa module, or plug-and-sense devices that are expensive and not flexible for deployment. WaterGrid-Sense comes as a full-stack node that includes a single PCB, processing unit, power management unit, two transceiver interfaces, and sensor interfaces, at a small size design. The node provides a wide range of usage for different applications. Moreover, WaterGrid-Sense is in twofold it supports two communication technologies: short-range communication IEEE 802.15.2 at 2.4 GHz, and long-range LoRa communication at 868 MHz.

3.3 Sensor node developments

In the new era of IIoT, the development of sensor nodes has become more attractive for most researchers and developers. The nature of deployments on industrial wireless sensor networks (IWSNs) requires sensor nodes that can handle harsh environmental conditions. Therefore, when designing a sensor node, size and communication technology employed are important.

Gungor *et al.* [65], explored challenges involved within IWSNs. With a focus on node design challenges and ways to overcome them, they defined some design principles that are best suitable for IWSNs and described technical approaches to help researchers and developers (R&Ds) when designing sensor nodes for IWSN deployments. Some of the challenges identified with IWSN nodes are that they are resource constrained due to their physical sizes; they are bound to the small power supply, limited memory, and processing capabilities. Dynamic topologies and harsh environmental conditions may be addressed by adaptive network operations. Harsh environments can cause node failures and network interferences, which require the network to adapt and continue functioning without other nodes, but capabilities to notify the network operators about node failures, are necessary for IWSNs. Large-scale deployments and ad-hoc architecture are other challenges in IWSNs. Hence, the need for low-cost, small sensor nodes that are able to self-configure and organize in terms of failures and scalability. To be able to scale the WSN, scalable architectures, and efficient protocols should be employed to address the integration of new networks with existing networks. The ability for sensor nodes to harvest energy from their surrounding environments has been mentioned a lot in literature, for prolonged WSN node lifetime and a reduction of network maintenance.

Stoopman *et al*, [67] presented a system and circuit design, of an external radio frequency (RF) powered 2.4 GHz-based CMOS transmitter that can be integrated into modern autonomous wireless sensor nodes. The transmitter uses the dedicated RF signal for energy harvesting and frequency synthesis. Thus leveraged RF used for frequency synthesis eliminates the need for inductors in the circuit design, hence enabling the low-complexity, low power, and area efficient solution. They used a nanowatt power management unit to enable sensitivity and long wireless range RF-powering. The external energy harvester captures electromagnetic (EM) energy and converts them to direct current (DC) power that is supplied to the Tx. The Tx consists mainly of two on-chip components, the power management unit, and frequency synthesizer unit. The power management receives power through the 915 MHz antenna and which also connects to the frequency synthesizer for further operations and output to the 2.44 GHz Tx antenna for communication. Moreover, they concluded that the complete Tx operation consumes 1.46 mW during on-off keying (OOK) modulation at 0.5 Mb/s, which is relatively small energy consumption at higher data rates.

Liu *et al*, [68] described a low-power sensor node designed to address the challenge of monitoring building temperature and light intensity for energy-efficient building design. The sensor integrates detecting light intensity, temperature, motion tracking, and compressive image acquisition in a single board. Moreover, they proposed a model for power dissipation and throughput of motion detection. A low-power and high-throughput algorithm that is hardware-friendly and optimized for motion detection was implemented. To test an Opal-Kelly XEM3010 FPGA board was used for imaging and motion tracking performance. The performed analysis was against traditional motion detection algorithms and found that throughput could be increased by 45%. The sensor node employs 3M2P standard CMOS technology, sizing to 3 x 3 mm squared silicon area. They also employed a 32-bit AVR MCU to control the sensor node chip. Lastly, they note that an adaptive algorithm can be developed for catching moving objects at a higher speed range.

Lu *et al*, in [69] engaged in developing the world's smallest sensor node with ultralow power consumption, in terms of both electrical block integration and physical interconnection point-of-view. Their work focused on exploring applicable practical approaches for green sensor node integration with existing systems and assembling them. To archive the world's smallest node, they introduced the buried pump interconnection technology. Their node is a customized IC coupled with signal processing and data transmission, and it has a universal interface for sensors and power management units. They fabricated the IC by using the 1P6M logic process. The achieved node size is 3.9 mm x 3.9 mm x 3.5 mm; initial setup in their experiment is humidity and temperature sensing. The node is said to also have a general purpose interface for analog and digital sensors, this means the node is not limited to any type of sensing application. The design specification followed with their node was to enable ultra-low power consumption, layout-free installation, and universal standardization and these design goals are emphasized in [1]. The investigation showed that the configuration of the designed sensor enables easy assembly with stand-alone power source and flexible antenna for the vast majority of applications. The authors also designed a novel algorithm to save energy by shortening the length of the frame transmission duration. The power consumption was evaluated using coin batteries. The frequency carrier employed was 315 MHz operating under license-free bands in Japan.

Paul *et al.*, in [70] demonstrated an always-on always-off energy-harvesting wireless sensor node that features a near-threshold voltage IA-32 microcontroller. The goal of the design is based on edge computing, hence, they tightly integrated sensor interface, an onboard processing unit, and onboard communication unto a single board. They noted the importance of developing such note at an mm-scale form factor, meaning they would not use an onboard battery, but energy-harvesting techniques or sources due to their sizes. Moreover, the node is based on a 14-nm tri-gate CMOS technology and use Bluetooth low-energy radio communication. In addition, the node harvests energy from the 1-cm^2 solar cell, which is enabled by the onboard power management unit for battery-free operations. Their tests were based on energy-efficiency of the node and they concluded that a functional AOAS utilizing the NTV MCU shows great results for maintained microwatts operation.

Cheong *et al.*, [71] described a wireless sensor network node based on ZigBee technology for ultraviolet detection of flame in WSN safety applications. The flames are characterized using a spectroscopic technique. For low cost, small size design, and higher reliability, the authors used nanotechnology. The components of the designed node are UV photodetector, ZigBee transceiver both coupled to a current-sensitive middleware front-end consisting of four components: high gain amplifier, logarithmic amplifier, ADC, and MCU. The MCU controls the ADC for mixed-signals and sends data to ZigBee transceiver through UART. The transceiver uses 2.4 GHz ISM. Their investigations resulted in the node detecting flame, on average, at 70 ms and power consumption of 2.3 mW from the 3.3 V supply.

Kan *et al.*, in [72] designed and implemented a small sized wearable inertial sensor node for body motion analysis. To achieve the smallest node size as possible the authors mentioned that they printed an Inverted-F antenna and integrated it on a four-layer PCB. The node is composed of TI's MSP430 microcontroller unit (MCU) and the CC2420 ZigBee based radio frequency (RF) chip for the antenna. Their node operates in 2.40 to 2.48 GHz and employs open source TinyOS for WSN. Moreover, their node is only suitable for body motion analysis and power dependent for other applications though it offers configurations on power management to meet other applications.

Somov *et al.*, in [73] discussed and designed real-world wireless sensor node for gas sensing. To evaluate their sensor, they compared it to an identical platform that uses the Wheatstone bridge. The work sorely focuses on power-aware gas sensing as the note that gas sensors contribute a lot to power consumption. To reduce power consumption, the authors used a voltage divider instead of a traditional Wheatstone bridge. Secondly, they used a four-stage heating profile for further optimization of power consumption in contrast to two-stage pulse heating in the Wheatstone bridge sensing circuits. Moreover, the designed node consumes 30% less energy than other platforms that were in comparison.

Chen *et al.*, in [74] proposed a novel sensor node, called Multi-Module Separated Linear underwater sensor node to operate in underwater wireless sensor networks (UWSNs). Their focus was on robust coverage and good communication performance. Hence, they proposed multi independent sensor modules on a single sensor node board, compromising cost for performance. Moreover, the node is based on multiple input single output (MISO) designs since it encompasses multi-sensor modules that communicate with a single header module and single header transceiver.

Imran *et al.*, [75] investigated the use of SRAM-based field programmable gate array (FPGA) design for duty-cycled wireless vision sensor networks. Their paper presents a low-complexity, energy efficient, and reconfigurable vision sensor node using a design matrix, which includes task partitioning between the server and the node addressing both processing and communication energy consumption. Moreover, their investigation shows that SRAM FPGA-based nodes can use duty cycling for energy efficiency. The node lifetime is 3.2 years on a 37.44-kJ energy battery.

In this review, we focused on any form of node designs mainly for WSN. All the reviewed literature emphasized in node power consumption as noted as an important aspect by authors in [65]. Authors in [67] and [70], used energy harvesting techniques from external sources to power their nodes. Authors in [67] harvest energy from surrounding magnetic field and convert it to DC to power the node whereas in [70] the energy harvesting is from a solar cell. Moreover, both nodes include a power management unit within the IC. Harvesting is advantageous to wireless sensor nodes because they are deployed in environments that provide energy harvesting. Therefore, this technique prolongs node lifetime in terms of power. Another important aspect emphasized by authors in [65] was node size. The smallest node was observed in [69], which is developed for green gas sensing, the authors also developed an algorithm for energy conservation. Moreover, the developed sensor node utilized the CMOS technology since it is good for integrating diverse sensing capabilities, signal processing on a single board [68], and realized as a building block for energy efficient node design.

3.4 WaterGrid-Sense Architecture

This subsection initially gives an overview of the LoRa network stack. We then narrow the discussion to the architecture of the node itself, through discussing the major components that make up the device, the next subsection discusses the device operations.

3.4.1 WaterGrid-Sense

WaterGrid-Sense is a LoRa based device, currently used in a smart water management system (SWMS). The SWMS is a combination of different components working together to form a flow sequence of a complete system. The network stack used for SWMS is a three-layer network stack as depicted in Figure 3.1. However, we will focus more on the perception layer of the stack, which consist of end-devices (EDs) or sensor nodes in this case. The communication medium used between the perception layer and abstract layer (Gateway) is a wireless communication. In addition, between abstraction and application layers different high-speed media can be used i.e. 3G, IP. The system deploys a low power wide area network (LPWAN) technology called LoRa as a PHY layer, which uses LoRaWAN communication protocol between the gateway and the ED.

WaterGrid-Sense is a LoRa based device using Microchip module and ARM MCU and it is a smart interface platform with the ability to monitor and control in real-time the components involved in SWMS. It provides a great variety of usage and can fit for different applications. The node is in two-fold communication technologies: short-range communication based on IEEE 802.15.4 that use 2.4 GHz and long-range communication based on LoRa/LoRaWAN using 868 MHz, hence, a flexible device can be used to fit different cases.

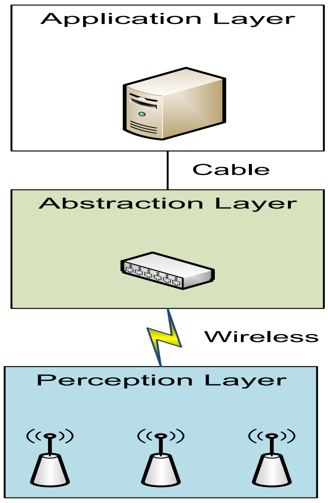

Figure 3.1: Layer Stack for Lora Networks

3.4.2 WaterGrid-Sense Device Components

The device is a full packaged stack with an onboard LoRa module using LoRaWAN™ Class A protocol stack, sensor interfacing, onboard processor, memory and finally onboard battery and solar interfacing, which are the main component of the LoRa device (ED) to function in a LoRa network. Figure 3.2 presents a block diagram featuring the major components. Moreover, below is a description of some components found on WaterGrid-Sense:

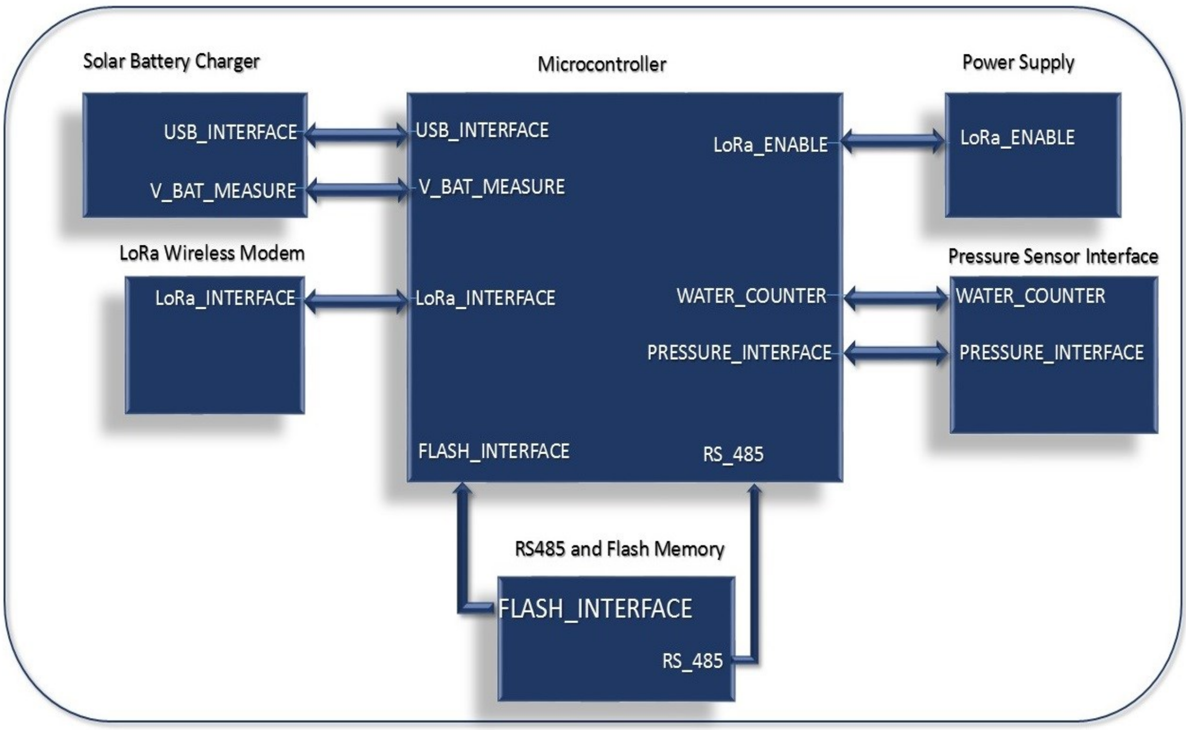

Figure 3.2: Block Diagram WaterGrid-Sense

i. **LoRaWAN Module:** *Microchip RN2483*[33] low-power long-range transceiver is used for LoRa communication. The module has onboard LoRaWAN Class A protocol stack; it uses UART ASCII command interfacing that allows configuration and firmware loading or upgrades. It provides low power consumption, which is the goal of LPWAN based devices. In addition, it allows programmable RF communication for GFSK and FSK modulation at a bit rate up to 300 bps, and for LoRa CSS modulation that is the bit rate currently used, up to 5.468 kbps. The Microchip RN2483 has a built-in microcontroller (MCU), Crystal Oscillator, EUI-64 Node Identity Serial EEPROM, radio transceiver with analog front-end and lastly 14 GPIO pins for control and status. The chip is a stand-alone device able and interfaced to any circuit through the available GPIO. It has built-in low-power long range transceiver operating in the 433 MHz and 868 MHz frequency bands. Its receiver sensitivity can go down to -148 dBm and the transmission power can reach up to +14 dBm which both makes the LoRa module transmission robust to interferences[33]. The module allows transmission up to 15 km in environments with low interference and objects but only up to 5 km in more harsh environments [33].

ii. **Microcontroller Unit:** The WaterGrid-Sense executes instructions programmed into the device through the main MCU integrated into the PCB. The used MCU is the *STM32L151RCT6A* [76], which is an ultra-low-power ARM Cortex –M3 high performance based MCU. This type of microcontroller is suitable for a wide range of applications in embedded systems, for our case, we use the device for wireless sensors. The ARM can handle the power of the USB for programming or loading instructions into the MCU. It incorporates 32-bit RISC core operating at 32 MHz, a memory protection unit (MPU), and high-speed embedded memories with flash memory of 128-kb and RAM up to 16-kbs. Moreover, it consists of enhanced I/O and peripherals connected to two APB bus which is one of the protocol specifications for AMBA [76]. The MCU supports four different advanced communication interfaces which are: SPI for data exchange between small peripherals, shift registers, and sensors, I2C for local components communications, USART, which uses the RS-232C protocol to facilitate Synchronous/Asynchronous Receiver/Transmitter through the serial ports of the MCU, and finally the USB, which in this case, is used to configure and load instructions to the MCU.

iii. **Pressure Sensor Interface:** The pressure sensor interface is an on-board female port, which has five ports for pressure sensor interfacing. The first port is for 5V voltage supply, SCL clock line is used to synchronize data transmissions over the I2C bus. In addition, the SDA is the data line used to transfer data.

iv. **Pulse Sensor Interface:** The pulse sensor is a three-port interface with 3.3 V for voltage supply, ground, and the pulse sensor input. The pulse sensor is interfaced with the analog Reed switch, which produces a pulse for water that passes through the meter. The Reed switch differs in reading the system uses the 10L Reed switch that produces a pulse each time after an amount of 10L has passed.

v. **Programming and Debug Header:** Programming and debug header is six male pins used to load LoRa network instructions to the WaterGrid-Sense. The instructions are loaded through the ST-Link interface that has an LCD and USB interface connecting to a computer for the transfer of instructions. The header pins work hand-in-hand with the onboard two-boot pin, in which a header cap has to be present in order for the header pins to be programmed.

vi. **USB_MINI_B:** The USB Mini B interface is used to configure the ARM MCU for the device use case, for example, we can set the SI unit for pressure readings from the sensors, and how the MCU processes the obtained data. It can be used to set up time and time formats, it can also be used to configure how many times should the data be transmitted in a day and after how long. This interface is not to be confused with the programmable header pins.

vii. **LEDs:** The LEDs can be used for different cases, for example, while testing the device the LEDs can be used to check the health of the device. They are labeled D2-D5.

viii. **I/O protection:** It is one of the important internal components in support and responsible for input and output.

ix. **Data Flash Memory:** Data flash memory for our device holds all data that has been transmitted via the LoRa module to the gateway, and the data can be accessed at a later stages from the memory, though it stores the data for a certain amount of time.

x. **Microswitch tactile:** The device has two onboard switch buttons the reset and the user buttons. The reset button can be used to reset the device to its initial state.

xi. **Boot pins:** Boot pins are the two male header pins and their act is a completing circuit point; in order for the device to function the cap has to be present. The device cannot be programmed or the instructions cannot be loaded into the device if the header pin cap is not present on the boot pins.

xii. **Header Friction Lock:** This component is used for actuation purposes. However, the SWMS does not utilize this feature. The application at hand focuses on monitoring of water usage.

3.5 Functionality

Functionality in our context describes the interrelation of the components involved in making the device and network achieve that which it is intended. We describe functionality in terms of operations of the major components involved in the sensor node. Firstly we present the general operations describing the abstract components involved, and lastly, the internal operations describing how the internals correlated and corporate to make the device function.

3.5.1 General operations

WaterGrid-Sense is based on long-range communication based on LoRa using 868 MHz and 433 MHz. However, now the device only uses the 868 MHz communication due to the setup of the SWMS, the deployed nodes are in long-range contact with the sink (gateway). In order for the device to transmit the acquired data, an external LoRa compliant antenna is attached to the device through the onboard antenna interfacing, which establishes a link with the gateway. The device is powered by a Li-Ion battery and harvests external energy through a solar panel. The node is designed to save energy at all costs to increase the battery life, LoRa itself makes sure that the battery lasts longer through the nature of the network deployment setup which uses ALOHA topology (star topology) and allowing nodes that are not transmitting data to enter a sleep mode to save battery energy. The device is designed to use solar energy to charge the battery during the day when there is sunlight. At nighttime, the node runs on the battery source. The battery voltage is 3.7 V, with a capacity of 1000mAh, the maximum charge the battery can handle is 4.2 V at 500 mA. WaterGrid-Sense currently has two sensor interfaces, which is a pressure sensor that uses the I2C intra-board communication for data transmission from the pressure sensor attached to the meter to the WaterGrid-sense interface. The pulse sensor which is attached to a water Reed switch on the actual water meter, the pulse magnetic field, sends an analog signal to the pulse sensor interface on the WaterGrid-Sense, the signal gets converted by the onboard analog to digital converter to be understood by the digital devices involved in the network. Both the sensed signals go to the ARM Cortex for processing before it is transmitted to the LoRa gateway via the LoRa module embedded on the WaterGrid-sense.

3.5.2 Internal operations

The internal functionality of the device involves the inter-communication of all components integrated on the board in order for the device to serve its purpose. The major components of the device are the input interfaces, the processing unit, and the output interface. In support of the major components, we have supporting components that protect the device and regulate the functionality of all other components such as voltage regulator, as we would expect all circuits to be well constructed. Once the data gets in from the sensors to the sensor interfaces, if necessary an internal analog to digital converter (ADC) is triggered to convert the data, and it is then transferred through the circuit network using the I2C communication protocol, which is a short distance communication protocol, intended to be used by digital integrated circuits. The data is sent to the ARM MCU for processing using the defined configurations to be done on inputted data. Once the data is formatted by the MCU for LoRa to use, it is transferred to the microchip LoRa module for transmission to the gateway; it then goes to the transceiver and finally gets out of the device through the antenna.

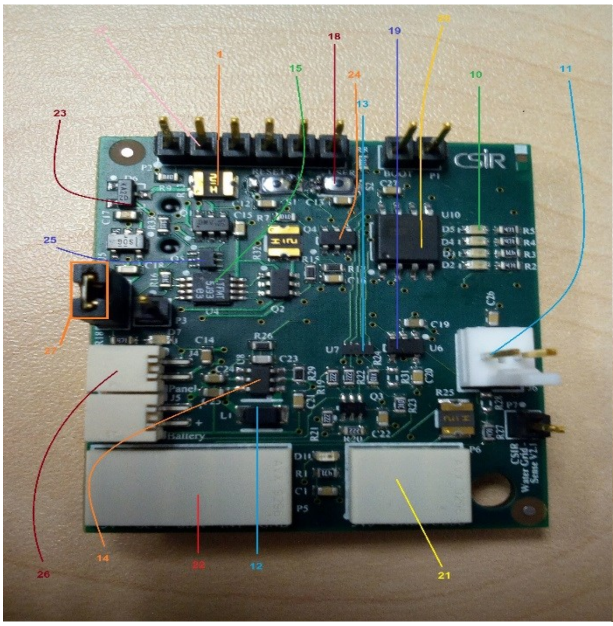

Figure 3.4: Top View WaterGrid-Sense V2.1

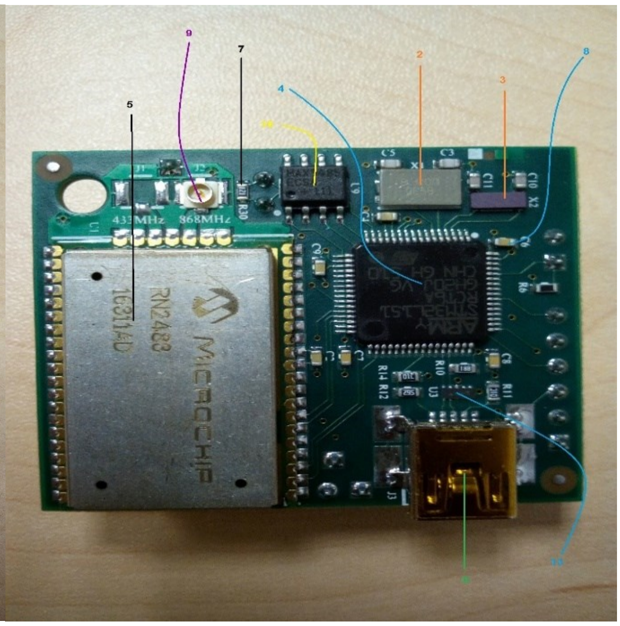

Figure 3.3: Bottom View WaterGrid-Sense V2.1

3.6 Handling

This subsection discusses the handling of the WaterGrid-Sense to connect the node to the network. We give a brief description of the node interface with the water meters and how it is manually configured to join the network, through parameter settings. Moreover, the necessary configuration steps are presented.

A. Interfacing the mote with the water meter

Currently WaterGrid-Sense interfaces with four components for water meter application: the battery to power up the device; the solar panel to charge the battery during the day with the energy from the sun; and finally the Reed switch, which connects to the meter used to monitor usage of water within the campus. The Reed switch is attached to the meter and connects to the device via a cable. The device and the battery are placed inside a small package; the solar panel is exposed to the sun by attaching it to the enclosure. Finally, the antenna is attached on top of the enclosure for better line of sight between the LoRa gateway and the device. The enclosure is made of metal and mounted on top of the water meter. The device and battery-packaging box are placed inside the enclosure. This is a safe way of packaging the motes as it protects all the components from being damaged be it from people or natural disasters.

B. Device connection to the network

Connecting the device to the network requires first, the device to be configured with the proposed network set parameters or in particular, the device is configured in relation to the gateway it is going to connect to. The first step is to make sure that all the needed interfacing is present, that is the antenna, and the battery is plugged into the device. Then we plug a USB cable into the device for network configuration.

C. Device configuration

When first connecting the device to the network, we have to configure the device through a USB interface. This step is required to flash the settings for water metering application to the device. The currently available settings used are to set the present water meter reading, set the clock date and time, and set the water counter multiplier. The first step is to make sure that the device is not plugged into the device used to flash in the settings; a reset button found on the device has to be pressed to make sure that all the data that might be present is totally erased and new data can be added. The second step is to plug in the device to the laptop (if used to configure), then start the configuration program through the serial terminal by running the following command *sudo minicom –s* this command starts a minicom serial port communication program [77] that enables configuration to WaterGrid-Sense. Once the configuration program starts, to access the menu "?" is pressed and the menu shown in Figure 3.5 appears:

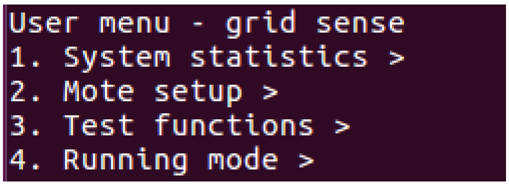

Figure 3.5: WaterGrid-Sense configuration menu

Option (1) from the menu is to show the system statistics, the system log, for example, the amount of data sent to the gateway.

Option (2) is the most important in our case we use it to reconfigure the device, settings available within option 2 are to view the mote settings as shown in Figure 3.6**.**

2.2. Program clock, date and time: which set the RTC time to the current date and time of configuration.

2.3. Program water reading: configure the water reading values to the device as it appears on the water meter.

2.4. Program packet sends interval: configure the interval at which the data is sent to the gateway, data is sent after every 10 minutes.

2.5. Program water counter multiplier: it is to set the water multiplier and the water pulse (Reed switch) i.e. influences the value of the multiplier if the used reed switch is for 10 litters the water counter multiplier is set to 10. To configure one of these settings a user has to press the corresponding number option.

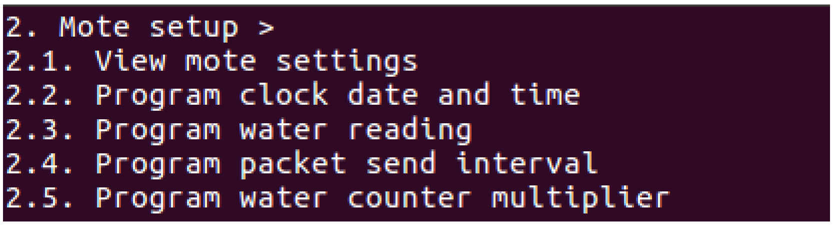

Figure 3.6: Mote Setup Menu

Option (3) from the main menu, is for testing purposes, it contains test functions. Option (4) ensures that after loading the entire configuration, the device activates the normal running mode and joins the network. The submenu within option (4) includes Enable USB <> LoRa bridge mode, Enable normal running mode, Enable test over the air commands mode and finally Disable timeout to running mode. After the entire configuration, we enter submenu "2" Enable normal running mode, to let the device go to its normal running mode.

3.7 Communication

The SWMS is composed of two types of networks; the public network using a public gateway that belongs to LoRaWAN service provider and the private network using CSIR owned gateway. In this work we focus on the private network.

A LoRa network uses a three-layer stack as shown in Figure 3.1 the communication between the LoRa EDs and the GW is using LoRaWAN protocol. From the GW to the network server, communication technology of choice can be used depending on the application a LoRa network is being applied on. For SWMS backhaul, we used two technologies to provide connectivity between the gateway and the back-end system; TV white spaces (TVWS) fiber optic link (see Figure 3.7**).**

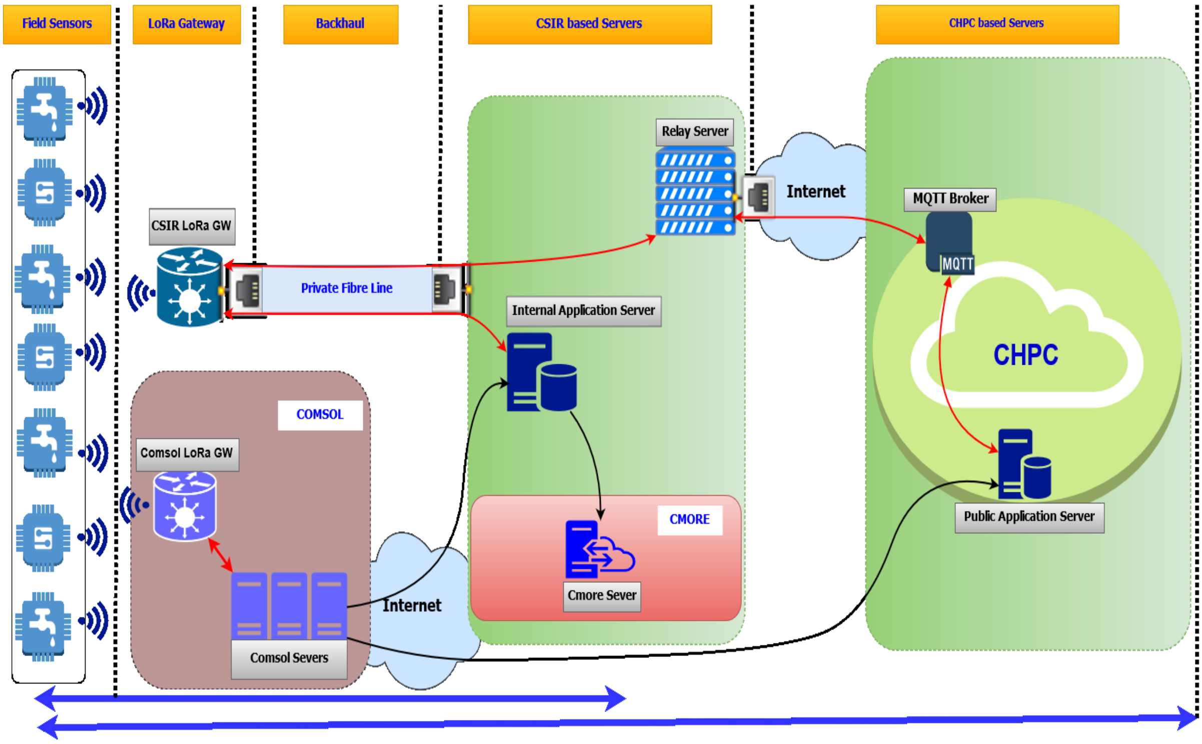

Figure 3.7: Traffic flow between sensor motes and the server

The ultra-high frequency TV (UHF TV) band is currently used for digital terrestrial television (DTT) broadcasting and Programmed Making and Special Events (PMSE), however when allocating spectrum to these units, there is a gap left in between these primary allocations, because high-power TV broadcast using the same frequency need geographic separation in between their coverage areas to avoid interference. The space left between these allocations is called White Space (WS) and can be used by different devices transmitting at lower powers than DTT. In the UHF TV bands, the space left in between DTT, local TV, and PMSE is specifically called TV white space (TVWS). This is the combination of locations and frequencies in the UHF TV band and new users can leverage this spectrum for their application purposes but in accordance with making sure that there is no interference to primary services surrounding that TVWS [78].

In a smart water management system, the communication between the GW and the network server leveraged the TVWS available in CSIR; a dedicated point-to-point (P2P) TVWS links the sensor network to the server. To form this backhaul link a TVWS customer premises equipment (CPE) links the TVWS base station (BS) and the LoRa GW. The GW and the CPE are interfaced to each other with an Ethernet cable and they are located at a Tower within the CSIR campus. A directional TV antenna is mounted to the CPE and links to the BS. The BS is located on the rooftop of Meraka building with a directional TV antenna mounted to it and pointing towards the Meraka-Tower. The Geo-Location Spectrum Database (GLSD) [79] that is connected assigns the communication parameters, frequency, power, location, and channels, to the BS. The operation frequency is assigned by the GLSD based on the location of the BS and the CPE. However, such frequency will be a specific 8 MHz channel within the UHF TV Band, between 470 MHz and 696 MHz. Currently, channel 24, with a centre frequency of 498 MHz, has been assigned. The BS has an internet connection to communicate with the GLSD. In addition, the distance between the CPE and BS is approximately 300 metres and the link path profile was calculated as shown in Figure 3.8. However, since the BS and CPE are firmware proprietary (©Carlson Wireless) some of the parameters may differ. The link between the BS and the GW is a Master and Slave architecture. The BS acting as the master, obtains operational parameters from GLSD and manages the communication between its slaves the GW, and CPE. The GW is able to operate under the TVWS under the control of the BS [78]. This innovation brings about showcasing the ability of spectrum sharing for different technologies. In this case, we use low power operating devices to avoid interference with the primary bands allocated to TV broadcasting.

3.8 Link Path Profile

The smart water management system is deployed at the CSIR campus and nodes are attached to water meters around the campus. The environment consists of trees, tall buildings, hills etc. hence we regard the deployment setup as deployed in a harsh environment. This allows for testing of different network aspects. One of the most important network aspects for wireless communication networks is the link budget. The link budget in a wireless system presents the strength of the signal at the receiver as it has traveled from the sender through the propagation channel. Every communication medium has effects on the message being transmitted. The link path profile, in this case, is composed of all the effects on the signal as it travels through the medium, all the gains, the losses including gains and losses associated with the antenna, surrounding networks, distance in between the transmitter and receiver, obstacles in between etc.

To determine the link budget between wireless links, equation (1) is used:

$$P_{rx}(dBm) = P_{tx}(dBm) + G_{system}(dB) - L_{system}(dB) - L_{channel}(dB) - M(dB) \quad (1)$$

where:

- P_{rx} = expected power loss occurrence at the receiver
- P_{tx} = the transmitter power
- G_{system} = system gains such as those associated with directional antennas, etc.
- L_{system} = losses associated with the system such as feed-lines, antennas (height of an antenna) etc.
- $L_{channel}$ = losses due to the propagation channel, either calculated via a wide range of channel models or from empirical data
- M = fading margin, again either calculated or from empirical data

Link budget of a wireless network link can be affected by many factors, for example distance, obstacles, external network interference etc. however LoRa is a leading LPWAN amongst others because it has good sensitivity, low path loss, and good obstacle penetration, making LoRa a robust and disruptive technology for long-range and smart city deployments where transmission conditions are constrained [80].

The Chirp Spread Spectrum (CSS) modulation technique plays a significant role in the sensitivity provided by LoRa. It trades data rates for sensitivity within a predetermined channel bandwidth. Spreading factor influences your sensitivity, the higher the spreading factor the better the sensitivity it provides with a fall back of more time on air (TOA) which requires close attention as LoRa has regulations on duty-cycle. For example, SF of 12 can provide a sensitivity of -134 dBm for a fixed channel bandwidth of 250 kHz at a coding rate (CR) of 2, but the TOA becomes 528.4 ms[80]. This is an outstanding performance provided by LoRa to be able to demodulate a signal at -134 dBm P_{tx}.

For the CSIR SWMS, we calculated every link between WaterGrid-Sense motes and the GW using an online link calculator called LigoWave[81]. As inputs:

1) name of each site where the GW and ED are located,
2) the selection of radio type if available automatically fills in the frequency,
3) transmit power and antenna gain of the radio
4) Longitude/ latitude,
5) The height of the GW and ED above the ground,
6) Rx Threshold,
7) Antenna polarization

The calculator then displays the results with a diagram as shown in Figure 3.8. The results show path loss, receiver signal level, thermal fade margin, link available, and the distance in between communicating network nodes [81]. A limited link occurs when after all the link calculation the incident power at the receiver is lower than the required, to meet the SNR requirement of the receiver in order to be able to demodulate the received data. LoRa, on the other hand, can detect signals up to -134 dBm below the noise floor.

Normalization is a process of adjusting the height of the Antennas in reference to the line of sight (LOS) shown on the LOS path after the calculation, this process is required to improve the link.

Figure 3.8: Link Calculation Results

3.9 Experimentation

The aim of this subsection was to investigate the battery life and battery usage of the device without the external solar energy source and to study its behavior during the initial communication routine when first joining the network. The study was carried out in a lab and conducted for a short duration.

3.9.1 Power Consumption

As highlighted, WSN has replaced wired networks to reduce maintenance and cost of deployment. However, while WSN reduces cost, their architecture deploys battery-powered sensors in a distributed and autonomous manner. Their lifespan depends mainly on the node source of energy, generally in most cases, batteries. Hence, the most important component in a WSN is the power source of each sensor node. For instance, in a mesh topology, every node acts as a core part of the network to relay data from the source to destination, if several nodes fail due to power constraints, the network gets affected on a larger scale because reconfiguration and rerouting of packets have to reinitiate. Therefore, as mentioned by authors in [65] to extend the lifetime of sensor nodes, power conservation, and management techniques play a significant role in sensor nodes design.

The simple power conservation and management techniques would be to have the sensor node set to operate in synchronous instead of asynchronous mode. To conserve power the sensor node should enter deep sleep at all times if there is no operation [82]. The node should only enter the active mode when it has a task to execute or when triggered in the case of monitoring and actuation. The power consumption of the sensor node is directly proportional to the active time of the sensor node [82]. This means there is always power loss/consumption when the node is in active mode. Power consumption starts from the sensors on the sensor node from the time signal sampling is done and converting that signal to electrical ones, to signal conditioning and ADC [65]. The other two major power consumption sources that contribute to a greater power loss are the processor and the transceiver, to minimize power loss contributed by these two components algorithms that decide where data is processed can be developed.

Depending on the type of radio communication used on a WSN, generally, a great amount of power is required to transmit data to the destination. Hence, utilizing algorithms in power management unit instills intelligence to the sensor node in terms of power conservation. The MCU should be able to determine in relation to the size of acquired data if whether it should be processed locally or on the server side. Usually, when the data is small the MCU processes it and transmits it in a shorter period of time conserving power on the transmission process whereas when the data is substantial it gets processed at the server side to conserve power on the processing task of the MCU. We expect WaterGrid-Sense to conserve energy out of the box since the design approach is system-on-chip (SoC) [65]. A power consumption study was conducted to measure how long the node could last if it operated only using the battery without the solar source. The results are presented in CHAPTER 5.

3.9.2 Communications Link

Industrial environments mostly consist of many obstacles that can temper with deployed wireless communication links. Hence, it is vital to deploy technologies that are able to handle such harsh environments. Otherwise failing to do so, compromises the reliability of the system at hand with respect to data transmission. Mostly IWSN is subjected to suffer noise, interference due to the nature of their environment, co-network existence, multipath propagation, etc. [65]. However, different types of applications require different types of communication links, even different environments influence the choice of communication developers will use. For example, real-time data will require links that are more reliable and can provide wide bandwidth and high data rates. During the power consumption study conducted, we also logged the data from the server side, in order to measure the reliability of the communication link when the device was located indoors and communicating with the gateway located outdoors. The results are presented in CHAPTER 5.

3.10 Chapter Summary

This chapter presented WaterGrid-Sense as a concept of IWSN and good practices of sensor node designs. The literature on IWSN sensor nodes revealed that the design of low powered nodes is still an ongoing research. Moreover, a public backhaul network link for the SWMS was presented to highlight how LoRa network supports different backhaul systems. The lab work for this chapter is presented in the results chapter under sensor node results.

CHAPTER 4

Research Design and Methodology

4.1 Chapter Outline

This chapter focuses on the design and methodology followed to accomplish the main goal for this research. The chapter begins with the system analysis, a discussion, and description of the actual network stack and architecture followed by data collection methods. Moreover, the environment of deployment and its impacts on the performance of LoRaWAN will also be discussed as well as the chosen evaluation metrics. We also discussed the proposed data visualization tool and the design of the test/performance evaluation scenarios that will be used to conduct a comprehensive analysis in the next chapter.

4.2 Choice of Research Design

The general discussion of the research design and methodology chosen for this research project is discussed in CHAPTER 1. This subsection describes the research design and details reasons why it is chosen and its advantages. In this research in order to realize and strengthen the goal of the project, to understand the theory behind the knowledge of the study, to identify research questions and objective, to know the research methods needed to be employed to achieve the goal, to identify analysis strategies, we utilize constructive research design which a problem-solving based research design [83]. Constructive research aims at producing new findings or solutions informed by theory and practical that undergoes. Moreover, it is used to identify or solve problems, also in the case of existing problems or systems constructive research aims to upgrade these systems or enhance performance. The main purpose of this research approach is to add or identify implications to the existing body of knowledge[83].

Constructive research is a methodological triangulation approach [84]; it employs both qualitative and quantitative methodology. It can be practical experience based or theoretical based or both. Which takes it back to the main goal of this research design, to identify and solve real practical issues. To achieve this goal, the process of this problem-solving approach utilizes the following phases:

a) Finding a practical relevant problem that has a research potential:
   There are several ways of identifying a research problem in constructive research, it can be experience based, an existing problem in a practical world or conducting an

survey of literature to identify the existing gaps. This phase is found in CHAPTER 1 of this study.

b) obtaining a general, comprehensive understanding of the topic:
   after identifying the research problem, the need for a comprehensive understanding of the topic is required. This can be achieved through extensive literature study and short experiments[83]. This study utilized a comprehensive literature review to understand the underlying body of knowledge and to identify the methodologies used, the devices used to conduct experiments, the evaluation criteria, and metrics used in literature. This approach was used in this study based in CHAPTER 2 and CHAPTER 3, and addresses the research questions Q1-Q3 and research objective RO1 in CHAPTER 1.
c) innovating – designing a new construct:
   The design of a new construct is pre informed by the prior extensive literature study and the realities of the problem at hand[83]. In this study we utilized a custom made LoRa device developed by the CSIR. Therefore, the research tools and methods chosen are tied up to how the device functions. As indicated we will develop a visualization tool that will help in giving the meaning to the data we are collecting. This is achieved CHAPTER 3 - CHAPTER 5 and addresses research objective RO2 in CHAPTER 1.
d) demonstrating that the new construct (solution) works:
   in order to demonstrate the working solution of a new construct the constructive research suggest that researcher use pilot testing, which is a small scale of testing before the major experiments undergoes[83]. For this work we performed a pilot test proposed in CHAPTER 3 and from the pilot test we were able gather meaningful information presented in CHAPTER 5.
e) showing the theoretical connections and the research contribution of the solution concept:
   Constructive research suggest that the conduct of the study should be inline with what is found in the body of knowledge of the topic and finally add to the body of knowledge. Basing the conduct in what is already there allows other researchers to replicate the study in order to check reliability of the contributions. The initial theoretical relations should be achieved through a comprehensive literature review of the latest developments which in turns helps to identify gaps and deduce research problems[83]. In this study the literature analysis done in CHAPTER 2 helped in identifying the research gaps, and further helped to identify and strengthen the research problem being

attempted. The uniqueness of this study lies in the duration of date collection, CHAPTER 5, reveals the hidden information that has not been possible in the existing literature and this is the contribution to the body of knowledge.

f) examine the scope of applicability of the solution:

Not every research output in a particular field solves all the problems of the identified problem. Constructive research requires that the contribution of study be scoped in the body of knowledge and sectors of applicability be identified[83]. This study in CHAPTER 1 clearly mentions that the area of applicability of this study is for networks deployed on harsh environments. Although, applicability to other scenarios can be drawn from the results in CHAPTER 5.

It should be noted that constructive design has its own short fall and disadvantages. Therefore, it cannot fit for all research problems. One of the major shortfalls is that constructive research cannot be applied in research problems that need forecasting. Hence, proper research designs should be chosen in such cases. Below we discuss the research methods and tools used in this research[83].

4.3 Research Methods

As stated in Chapter 1, the aim of this research was the evaluation of the performance of LoRaWAN network that is deployed in a real-world system setup and environment. Thus, this chapter discusses in detail the implementation approach, and the methods of investigation discussed in Chapter 1. However, to evaluate LoRaWAN; the performance measurements discussed in this research are solely based on the environment of deployment, although the focus will also be phased on the network configurations. In order to solve our problem, a flowchart of the methodology is shown in Figure 4.1, as well as the design methods and tools that were employed.

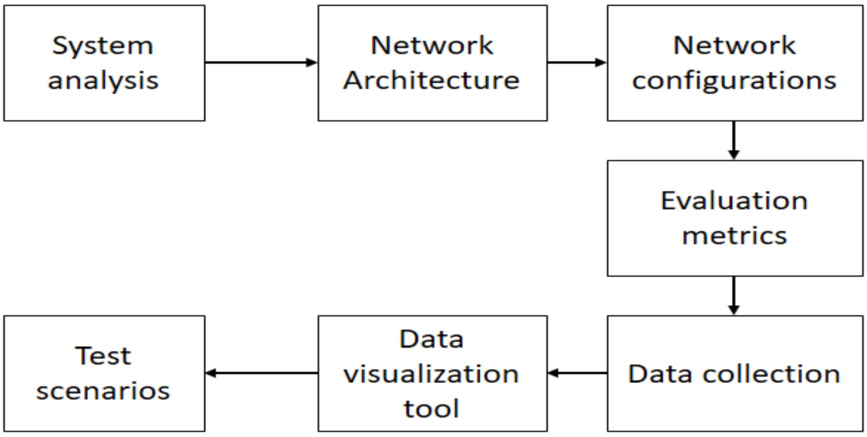

Figure 4.1: Research framework

The systematic methodology shown in Figure 4.1 is as followed.

1. A system analysis was carried out first and in the context of our research, system analysis involves a comprehensive analysis of LoRa technology stack including the WaterGrid-Sense a LoRa based device to gain an in-depth understanding.
2. Secondly, we proceeded with the detailed setup and tools required to understanding the network and its architecture.
3. Moreover, we looked at important metrics that can be used to evaluate LoRa stack. To this end, after understanding these metrics, we then selected the important metrics that are critical to this research.
4. Data plays an important role in the analysis and evaluation of a system hence a data collection method was formulated and discussed in details.
5. Raw data on its own is difficult to analyze and draw meanings from; hence, we developed a data visualization tool that presented the data in an understandable form and in a manner convenient for the comprehensive analysis required.
6. Lastly, as mentioned in the problem statement our tests are to be conducted on the data collected for a longer period from several end-devices (EDs). Thus, this data can be cumbersome to deal with; hence, we formulated the test scenarios that guided our analysis and evaluation.

4.4 Research Settings

In this subsection, we present the research settings. The system as mentioned in chapter 1 is deployed in a harsh environment. The environment qualifies this LoRa evaluation to be that of an industrial context. Hence, we used an IWSN node. The environment consists of buildings, hills, tree, other wireless networks, industrial machinery work, etc. The system deploys 34 nodes all communicating to a single gateway as shown in Figure 4.2. The gateway was placed in an outside environment where it tried to be in a clear line-of-site (LOS) with the entire deployed EDs. The gateway was placed on top of the hill located on campus as depicted in Figure 4.3. It shared the antenna stand with other antennas for different network purposes. The height of the antenna above the hill was measured to be 10 meters high. The elevation of the antenna improved LOS with the EDs. The node communication was set for 10 minutes intervals for each node.

Figure 4.2: CSIR private LoRa gateway

Environment of deployment: The environment of deployment plays a bigger role in attenuating wireless signals. As stated in the problem statement, this research was conducted in a harsh environment where some EDs were behind buildings, hills, trees, etc. They all constituted obstacles that could influence how well the devices communicated on the network. Wireless signals are always prone to these factors and some are inescapable, but measures can be taken to minimize the unwanted effects on the network performance. Moreover, having knowledge of how wireless signals are affected by the environment of deployment can help researchers or developers put good network planning measures beforehand.

Figure 4.3: Network Deployment Map

Amongst many factors that can affect the performance of a wireless network, in this work, we focused on the most common ones based on our deployment environment. We considered physical objects; in this case, the physical objects would affect the line-of-site (LOS) between the gateway and EDs. The network range is the distance between the gateway and an ED. We expect far devices to have weak performance than close range devices if there is LOS. The other common factor is the wireless network interference, this involves many things, and however, we would not focus on this factor in detail. In our case, more contributing interferences could be other networks operating around the campus. The other factor was signal sharing or sharing of the medium; this simply is the load on the wireless network. The more devices on the network the higher chances that it is of poor performance. LoRa is said to be a network that works fine around other networks. Moreover, it is also said to be robust to interferences and attenuations caused by aforementioned factors. Our study sought to evaluate how some of these factors affect the quality of LoRaWAN signals.

4.5 System Analysis

System analysis is an important activity that precedes other stages during system development. It is a key problem-solving technique composed of an in-depth understanding of the system components, and how they cooperate to achieve a defined goal. Carrying out this activity helps with identification of requirements and operations of the system at hand. To this end, researchers and developers are able to formulate procedures required to solve the problem, solely based on the knowledge gained from studying and carrying out the analysis of the system.

In the context of this research and in order to get familiar with LoRa technology stack and the device used in the network deployment, a comprehensive literature review was conducted to better understand the nature of LoRa network deployments, common applications, important metrics used in testing or evaluations, and network configurations. In this case, we conducted a review of sensor node designs to better understand the design of devices deployed for low powered wide area networks. The work is presented in CHAPTER 3 and CHAPTER 2, and Table 2.2 summarizes the findings.

4.6 Network Architecture

In this section, we present the network architecture of the existing water management system under analysis that has already been in place and operating. Its architecture is a three-layer stack as shown Figure 4.4 the perception layer, the abstraction layer, and the application layer. They are explained in details as follows:

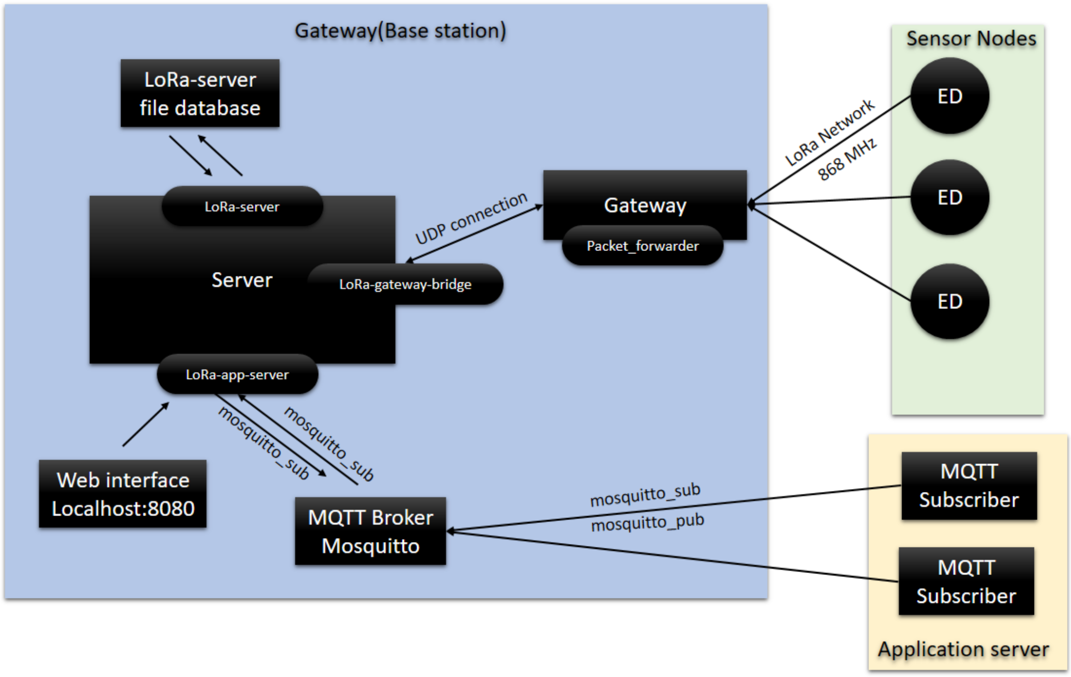

Figure 4.4: LoRa Network Stack

Perception Layer: This layer is discussed in detail in Chapter 2. It consists of the nodes, attached to each water meter across the whole campus. Each building has its own water meter and some meters serve different buildings at once. However, there are 34 motes in total. These EDs provide the network with data received from the water meters, the data collection subsection discusses how the data for this study is collected and categorized.

Abstraction Layer: This is a LoRaWAN network architecture consisting of gateways, used to relay data between the EDs and the back-end server. A LoRa network can have multiple gateways serving LoRa EDs, a setup that is scalable for large-scale networks. These EDs can be configured to send data to all the gateways; however, this can create a complex network and redundancy of data. Moreover, commonly used configurations involved linking the EDs with a specific gateway to relay data. In addition, sensors can be grouped into clusters or be grouped according to application specifics in the setup.

Currently, the system deploys a single gateway serving all the deployed EDs across campus in a star topology, which is referred to as ALOHA-based protocol in LoRaWAN. We utilized a programmable industrial IoT gateway called MultiConnect Conduit, as shown in Figure 4.5.

Figure 4.5: MultiConnect-Conduit

MultiConnect Conduit is a flexible gateway that offers configurability, ease of management, and communication scalability for industrial IoT. It has two accessory attachment interfaces that allow developers to attach the supported MultiConnect mCard modules for a wide range of asset connectivity for either wired or wireless communication. It allows supported attachment of connectivity modules of choice. The available interfacing supports data management through backhaul connectivity is 4G-LTE, 3G, 2G, and Ethernet.

Application Layer: This layer in the IoT three-layer stack architecture is composed of the destination for data. In our context, the application layer consists of the backhaul network server and the data presentation/visualization applications. It has different databases and application servers that received data from the same source located at the perception layer.

4.7 Network Configurations

Network configurations or setup involves the process of defining the nature and functionality of the network, the movement, and flow of the data within the network. It includes both hardware and software settings. In this study, the network configurations involved looking at the LoRa network parameter settings and the environment of deployment which are considered critical to the network performance.

LoRa network parameter settings: LoRa network configurations in this study are guided by the parameter settings as presented in Table 4.1. The configurations also span a wider range, which includes those done on the EDs, to the gateway, and to the NS. A discussion of the device settings is presented in Chapter 3 and the gateway is described in the architecture subsection. LoRa network operates in different frequencies across different regions, although the operations do not span out of the ISM-Bands for public usage. The International telecommunication union (ITU) divided into three regions we fall in region 1 that includes Europe and Africa amongst others. The frequency available to use for LoRa is on the 868 MHz band and this network parameter will not change once set or detected by the devices. The maximum transmission power parameter is defined by the region of operation and for region 1, the allowed maximum power transmission setting is 14 dB, for this parameter also, once set it becomes fixed until changed.

Table 4.1: LoRa Data Rates Correspondence

Data Rate	SF	Bit rate [kbps]	Rx sensitivity [dBm]
DR0	12	0.25	-137
DR1	11	0.44	-135
DR2	10	0.98	-133
DR3	9	1.7	-130
DR4	8	3.1	-129
DR5	7	5.4	-124

Table 4.1 presents the parameters that are allowed to be set by the user and have the ability to alternate accordingly. They include the data rate, the channel of communication, modulation technique, and coding rate. Data rate consist of two values the spreading factor (SF), and the bandwidth (BW). The spreading factor can alternate between values from 7-12 and bandwidth values can alternate between 125 kHz, 250 kHz, 500 kHz. Configuring the data rate for LoRaWAN means either setting the adaptive data rate on or off. Setting adaptive data rate on means the network will adapt to the nature of the link between the gateway and the ED and set the data rate accordingly. If the adaptive data rate is set to the off position, the user manually defines and fixes the value of both SF and BW and regardless of the nature of the link the network will transmit in this setting.

The disadvantage of not using the adaptive data rate is that some of the transmissions might fail because of poor link budget. Therefore, in this study, the network was configured to use adaptive data rates; this means the SF and BW would be alternating to fit the link budget between the gateway and each ED. The communication channels also could be preset for EDs to utilize. However, with the adaptive data rate enabled LoRaWAN allows the NS to allocate the communication channels that are not occupied on demand to EDs that need to communicate. Moreover, EDs can share a communication channel if they use different data rates; this means devices using different SF values can share a channel. This concept is known as orthogonality in LoRaWAN and it is one of the features that make LoRaWAN unique and a leading LPWAN. Moreover, this feature contributes to the sensitivity of LoRaWAN towards interference. LoRa physical layer supports the FSK modulation technique. However, when using LoRaWAN it is advisable to opt for LoRa modulation. Hence, this setting for our deployment is LoRa. Data rate correlates with SFs as shown in Table 4.1.

4.8 Environmental factors

Environmental factors are external parameters that are usually present in a wireless network that may hinder the network performance or can be leveraged to enhance the performance, this subsection looks closely in our context the factors available in our network deployment environment.

Physical obstacles: The signal strength is bound to effects caused by almost any obstacle between the transmitter and receiver, some obstacles can work on the signals favour some do not. Obstacles can reflect the signal redirecting it to the receiver or reflect the signal to the wrong path causing interference with other signals. Metallic and conductive obstacles, in particular, are largely reflectors of the signal. Some objects absorb the signal; this factor can limit the distance the signal travels and its power. Moreover, lower frequencies penetrate objects better and high frequencies on the other hand reflect the signal better. However, a clear LOS increases the reliability of the link and a clear LOS can be achieved by elevating the antenna higher enough to clear the Fresnel zone (Figure 4.6) from obstacles. The Fresnel zone is one of a series of confocal prolate ellipsoidal regions of space between and around a transmitting antenna and a receiving antenna system. We can define Fresnel zones the RF LOS as compared to visual LOS as viewed with the naked eye.

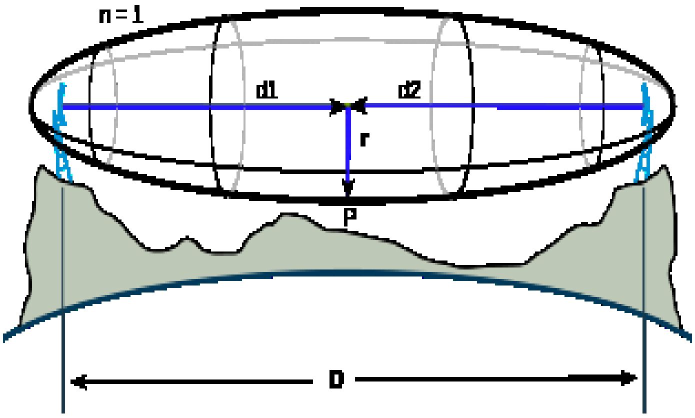

Figure 4.6: Fresnel Zone [85]

Network range: we define network range as the distance between the transmitter and the receiver wherein a connection is established. The range is also a function of data rate trading, higher data rates will result in shorter ranges, and lower data rates can reach longer ranges. Greater ranges produce weak signal strength, and shorter ranges produce stronger signal strength. This is due to the nature of signal propagation the signal spread as it travels through space causing loss of energy. Therefore, the more the signal spreads the weaker it becomes. Using high transmission powers can also increase the range; however, this is a challenge in IoT deployed due to the device constraints involved with WSN.

Interference: IoT is governed by wireless connectivity because billions of devices are expected to be connected and wireless communication becomes the cheaper way of connecting devices. This means that the communication spectrum is always occupied by transmission. Transmissions operating at similar frequencies are bound to interfere with each other and cause problems with their communication objectives. Signals operating on unlicensed like LoRaWAN are bound to collide with other signals operating on similar bands because almost anyone can deploy and start communicating. However, LoRa is said to be resistant to inference with other signals. Lastly, our network operates in an environment where other wireless communications are present as depicted in Figure 4.3.

The sharing of a medium: Wireless communications allow many devices to transmit and communicate at once, resulting in them sharing the communication medium. As devices present on the network increase the results in the network load increase. This factor can affect the performance of the network in a negative way. However, LoRa is able to host thousands of devices on a single network with a single gateway, without tempering the performance. This is possible because of the orthogonality provided by LoRa and the adaptive data rates managed by the LoRa NS. In addition, the use of duty cycle on LPWANs ensures that the spectrum is not overused by devices hence the load put in by each device is balanced. The duty cycle for LoRa is 0.1%.

Table 4.2: Network Parameter Settings

Parameter	Setting
Tx Power	14 dB
Frequency	868MHz
Modulation	LoRa
Adaptive Data Rates	ON
Channel Allocation	Automatic
Data encoding	Base64
Coding Rate	LoRa ECC

We discussed the technical configurations of LoRa, LoRaWAN and how the network utilizes them for this research and Table 4.2 summarizes the configurations and parameter settings discussed above. We further discussed the environment of deployment and the present factors that are bound to affect the performance of the network. This research analysis was based on the effect on the environment and not much on the parameters and the technical configurations.

4.9 Evaluation Metrics

This section presents the evaluation metrics used to assess the performance of the deployed network. In this research, we studied and identified the important metrics that are used to measure and evaluate the performance of LoRa networks and WSN in general. The metrics are based on LoRaWAN and LoRa characteristics and are commonly used to evaluate wireless signals. Moreover, the spreading factor is unique to LoRa, and for packet delivery ratio (PDR). Though it is a basic metric, it can also be defined differently for different systems. Thus, we defined the measuring parameters and their criteria as follows:

Received Signal Strength Indicator (RSSI): RSSI is the most common metric used in wireless links to measure the performance of the network. As the signal propagates in free space, it experiences attenuation, which can influence it positively by increasing the signal strength or negatively by weakening the signal through obstacles found between the transmitter and the receiver. This phenomenon is known as path loss. The relative signal measured at the receiver indicates the received signal strength after all the gains and losses have been applied to it this measurement is the RSSI, and is measured in dBm or sometimes as numerical percentages. Moreover, RSSI can be calculated using equation 2.

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2}$$

where: $\boldsymbol{P_R}$ *is the Power at the Receiver*

- $\boldsymbol{P_T}$ *Power at the Transmitter*
- $\boldsymbol{G_T}$ *Antenna Gain of the Receiver*
- **λ** *Wavelength (speed of light/frequency)*
- **π** *Pie: The ratio of a circles's circumference to its diameter, ~22/7*
- **d** *Distance in meters*

Signal to Noise Ratio (SNR): When the signal is propagated through space between the transmitter and receiver, it is exposed all kinds of signal noise, and if the noise overcomes the signal the receiver is not able to decode the right information from the received signal. Therefore, SNR is the ratio of the wanted signal to the noise present in the received signal at the receiver. SNR is an important metric as it determines at the receiver which data rates can be utilized in retrieving the information from the signal. The higher the SNR it represents good signal quality. Using equation (3) where signal is the desired entity and noise is the unwanted one.

$$SNR = \frac{Signal}{Noise} \tag{3}$$

Spreading Factor (SF): The data rates are mainly controlled through SF. SF is the LoRa modulation technique or feature that spreads the signal across the bandwidth in a form of chirps. The rate at which these chirps are spread across the BW is called spreading factors. Higher spreading factors present slower chirp rates resulting in lower data rates and this allows the signal to travel over a longer ranges. LoRaWAN uses adaptive data rates to ensure reliable signal transmissions by adjusting the spreading factors for the signal in transmission. SF also plays a bigger role in receiver sensitivity as shown in Table 4.3 below taken from Semtech data sheets. Far away, EDs are likely to use SF 12 through ADR to reach and achieve successful data transmission.

Table 4.3: Receiver Sensitivity According to SF

BW \ SF	7	8	9	10	11	12
125 kHz	−123	−126	−129	−132	−133	−136
250 kHz	−120	−123	−125	−128	−130	−133
500 kHz	−116	−119	−122	−125	−128	−130

Packet Delivery Ratio (PDR): Packet delivery ratio (PDR) is the ratio between the total packets sent by the ED and the total successfully received packets by the receiver. Using equation (4) below, if the PDR equals to one it means all the packets were delivered successfully. However, if there were some packets lost along the transmission, the received packets would be less than the sent packets. Moreover, received packets cannot be greater than sent packets, unless there was packet duplication and re-transmissions occurred from the ED.

$$PDR = \frac{received\ packets}{sent\ packets} \tag{4}$$

Where:

1) Received packets are the totals packets received by the receiver.
2) Sent packets are the total packets sent by the transmitter.

4.10 Data Collection

Data collection involves accumulation and classification according to the defined variables, as well as storage of data, in most cases in an ordered manner. In the context of this research, this process enables us to analyze, evaluate, and predict behaviour or make decisions from the insights gained along the process. In this context, data is collected in the form of network packets in an equally timely manner from each deployed sensor node. The packet received consists of the payload containing the user data, in this case presenting the water usage or/and pressure recorded from a pressure sensor attached to them, and the second class is network control data containing the configuration information of the network and the wireless link information generated at the receiver node (gateway). To this end, we can classify our data into two categories: water usage and network control. The data classification is important to distinguish between the main system which is the swms and the focus of this research which is on the performance of the network.

4.10.1 Water data

Based on the water management system under study here, each building has its own water meter used to monitor the usage around campus. Each water meter has a sensor node that senses and transmits data to the gateway and from the gateway; the data is relayed to the backend end-server for presentation and visualization. The SWMS dashboard application is shown in Figure 4.7, a stand-alone web interface application. Based on this application, broken pipes can be detected by an unusual increase in water usage in a certain location and action can then be taken and so on.

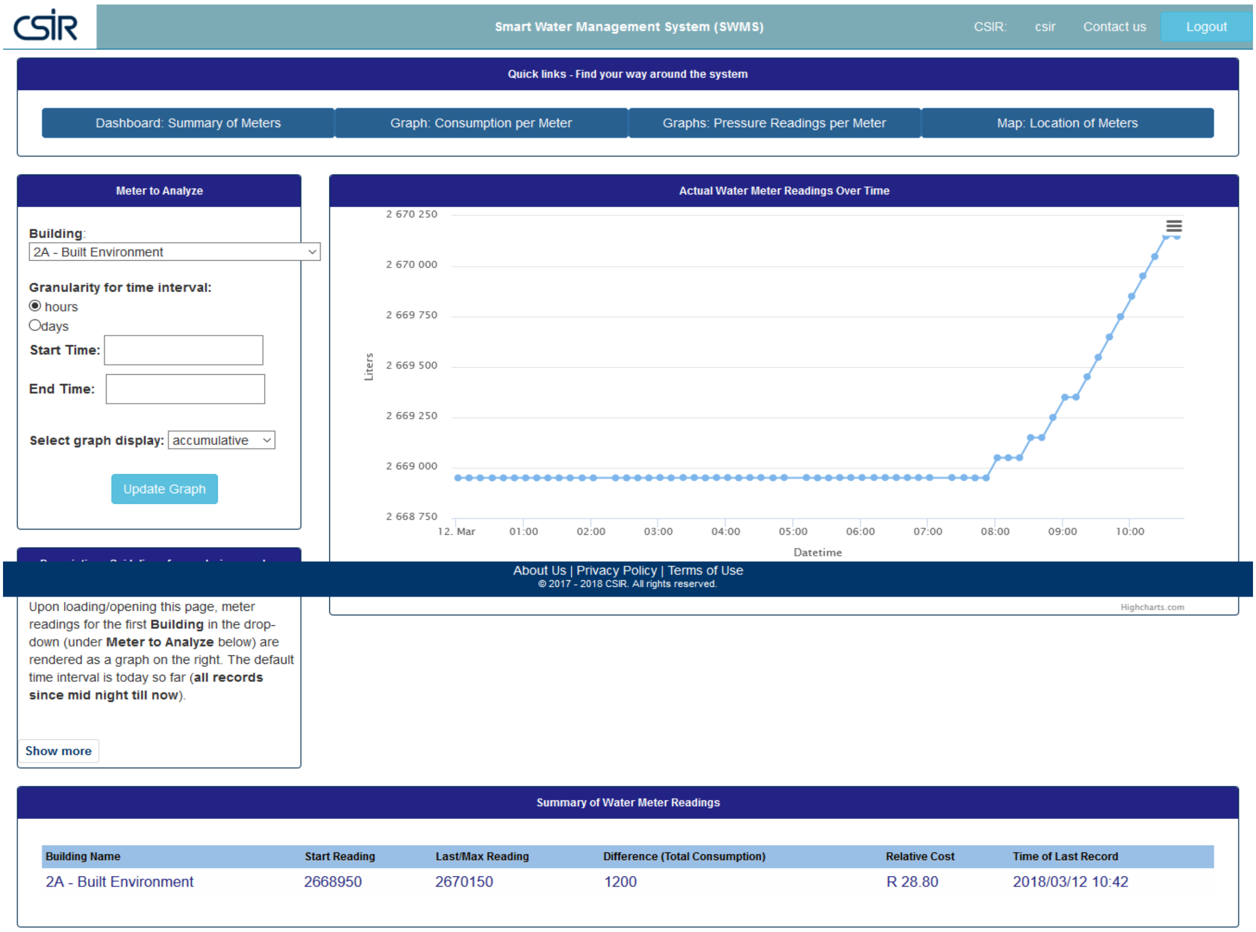

Figure 4.7: SWMS Dashboard

The EDs are configured the same, each node senses and sends the data after every 10 minutes. The node is configured to enter into the sleep mode when it is not in operation – efficient power conservation. The sensed data contains the current timestamp, current sensed water value, current sensed pressure value for nodes that have a pressure sensor, and the node mac address, which is mapped to each building name. Therefore, from the web interface, each building can be looked at in terms of its water usage. Moreover, the visualization on the web interface ignores any other data that came with the network packet in terms of visualizing it.

4.10.2 Network Data Collection

LoRaWAN features secure bi-directional communication between the gateway and EDs. The uplink is the transmission of EDs to the gateway and the downlink is the transmission from the gateway to the EDs. The downlink is a unicast process at most times, although a distributed control message can be scheduled from the network server (NS) to control or configure the devices connected to the network. A LoRa NS can only send a message to the node immediately after the node transmits, during the two-window receipt process provided by the node this is when class A is utilized, otherwise the LoRa NS has to queue the message to the downlink of a specific device and until the device transmits the message it remains in the queue. LoRaWAN communication is duty-cycled to 0.1% since it uses ISM-bands. Thus, a device is given a limited time to occupy a communication channel. This contributes to extended battery life for the sensor node and provides managed spectrum usage.

In order to collect network data, this research only focused on the uplink because the EDs were configured manually before deployment discussed in the previous chapter. In addition, the only downlink communication happening was time synchronization between the sensor node and the NS, which command was sent always immediately after a node transmitted if the time received by the NS was not coordinated. The uplink supported multicast, meaning a device would emit messages to any gateway reachable and, if the gateway acknowledged the join-command from the device it would always receive the transmissions from that end device. However, private networks are able to filter out the devices that do not belong to their network, mostly done through authorization or the network configurations. Moreover, public networks allow devices to join the network and create their own sub-topics.

The uplink stream consists of several transmission topics as classified by MQTT protocol. The MQTT broker is the application used to relay messages between the application servers (AS) and the NS. It is provided on the conduit to handle the network messages. Applications deployed on external servers are able to subscribe to different relevant uplink topics. When an application subscribes to the MQTT broker topics, it receives data in a JSON format. The applications can be written in any programming language. However, to pull the data from the broker there are several MQTT libraries in different languages that are able to interface with any deployed broker. For a device to join a LoRaWAN network it must initially send a join request on the uplink to the gateway, the gateway would then relay the message to the LoRa NS for join operations. The NS sends back a downlink acknowledgment message to the device if the ED met all the requirements of the network. From there the ED is able to transmit the sensed data to the NS. As mentioned, the uplink consists of several different topics as shown and described in Figure 4.8.

Event Topics

- up – occurs when a packet is received and authenticated. Will be sent to application only once for each frame counter. Duplicate or retransmitted packets will be filtered by the network server. Payload has been decrypted with the Application Session Key.
- down – occurs when an application submits a packet for downlink using MQTT
- joined – occurs when an end-device join request is received, validated and join response is queued. If join request was serviced by remote join server "remote_js" in JSON will be set true.
- join_request – occurs when a join request is received.
- join_rejected – occurs when join request is denied due to a mismatched AppKey, UnknownDevEUI or Gateway Mismatch.
- join_accept – occurs when a join request is valid and a response is ready to be sent.
- down_queued – occurs when a downlink packet is successfully queued by an application.
- down_dropped – occurs when a packet cannot be queued
- mac_sent – occurs when a set of MAC commands are sent to the end device in a downlink packet
- mac_recv – occurs when a MAC command is received in an uplink packet
- packet_sent – occurs when a packet is sent to the radio for transmission
- packet_ack – occurs when the network server receives an uplink with acknowledgement of successful receipt of a downlink packet.
- packet_drop – occurs when a packet could not be scheduled for transmission in an Rx Window and cannot be resent later, i.e. join request cannot be rescheduled or ACK retries have been exhausted.
- packet_missed – occurs when gap is detected in the frame counter of received frames. A count of the detected missed packets will be provided in the message.
- packet_recv – occurs when a packet is received and authenticated. Duplicate packets will appear, data payload is encrypted.
- queue_full – occurs when space is not available to queue a downlink for the end device
- class – occurs when an end device operating class is updated.
- clear – command sent to clear an end device downlink queue
- cleared – occurs when an end device downlink queue is cleared.
- gw_rejected – occurs when a UDP packet is received from an unknown gateway and a new record could not be created due to currently installed license information

Figure 4.8: LoRa Topics Description [86]

From the described topics in Figure 4.8, it can be seen that the topics described include the events generated from both the ED and the NS. In this study, we logged and stored only the uplink streams from all the ED's. However, the topic of interest for our analysis was the UP topic, which was described, as occurs when the packet was received, authenticated, non-duplicates discarded, and where the payload was encrypted with the application session key. The UP message/packet included the fields as shown with the prescription of each in Figure 4.9. In addition, the JSON payload received when subscribing to the broker is structured as shown in Figure 4.10 when using LoRaWAN revision version 1.4.

Name	Type	Function
time	string	UTC time of pkt RX, us precision, ISO 8601 'compact' format
tmms	number	GPS time of pkt RX, number of milliseconds since 06.Jan.1980
tmst	number	Internal timestamp of "RX finished" event (32b unsigned)
freq	number	RX central frequency in MHz (unsigned float, Hz precision)
chan	number	Concentrator "IF" channel used for RX (unsigned integer)
rfch	number	Concentrator "RF chain" used for RX (unsigned integer)
stat	number	CRC status: 1 = OK, -1 = fail, 0 = no CRC
modu	string	Modulation identifier "LORA" or "FSK"
datr	string	LoRa datarate identifier (eg. SF12BW500)
datr	number	FSK datarate (unsigned, in bits per second)
codr	string	LoRa ECC coding rate identifier
rssi	number	RSSI in dBm (signed integer, 1 dB precision)
lsnr	number	Lora SNR ratio in dB (signed float, 0.1 dB precision)
size	number	RF packet payload size in bytes (unsigned integer)
data	string	Base64 encoded RF packet payload, padded

Figure 4.9: LoRa UP topic payload description [87]


```
Payload: {
        "ack":false,
        "adr":true,
        "appeui":"99-99-99-99-99-99-99-88",
        "chan":1,
        "cls":0,
        "codr":"4/5",
        "data":"ExgEERY4AECZAA==",
        "datr":"SF12BW125",
        "deveui":"00-04-a3-0b-00-1b-e3-b9",
        "freq":"868.3",
        "lsnr":-6.2000000000000002,
        "mhdr":"8019000006821300",
        "modu":"LORA",
        "opts":"0303",
        "port":1,
        "rfch":0,
        "rssi":-111,
        "seqn":19,
        "size":16,
        "timestamp":"2018-04-11T14:36:41.681996Z",
        "tmst":859910676
    }
```


Figure 4.10: LoRa UP topic payload

The collected data was quite substantial for our purposes. One of the points from the problem statement was that previous researchers conducted their studies over short durations and their focus was on experimental tests, and rarely only focusing to achieve an application. For example, the system we conducted this investigation on is for monitoring water usage around the CSIR campus. It uses the LoRa network as a communication medium. In addition, the system has been running way before we started this study.

To satisfy our goal and address our objective we had to collect the data for an extended period. In this way, we were able to explore the behavior of this technology, to analyze and evaluate its performance for a longer period. The collected data was over a ten months period. This means the data collected included seasonal change data when the system was running. Moreover, the data were collected from 34 EDs.

The data collected were raw data from the system, there were no alterations, or a calibration before it got stored in the database. To obtain this data for storage we used a MQTT library written in python programming language called PAHO MQTT [88]. This library allowed us to interface with the system and subscribed to preferred topics offered by the MQTT broker. We wrote a script in python using this python library to interface with the system and map the obtained data values as shown in Figure 4.10 payload to the database rows and columns. In addition, as mentioned no data processing was done in this script. As can be seen, the performance analysis evaluation metrics derived for this study appear in the Figure 4.10 payload. The signal to noise ratio (SNR) abbreviated "lsnr" which stands for LoRa signal to noise ratio, the RSSI, and the spreading factor, which appears on the "datr" value, coupled with the bandwidth, the "datr" present the adaptive data rate discussed in the configurations subsection above.

4.11 System Development

To perform the analysis of the collected data, we needed to present it in a meaningful way. The purpose of data visualization is to extract insights. In our case, as part of the methods, we proposed to develop a visualization web-based application. The system is composed of several components first the script to collect the data from the gateway/LoRa NS. The second component is the relational database to store and organize the data in a structured way. The third component is the backend application connected to the database and performs some operations on the data to prepare it for the frontend component composed of charts displaying the data in a visualized manner. The developed software is a full-stack application that will assist with the comprehensive analysis and evaluation of the network performance.

A. Data Script

In order to interface with the network, we wrote a script using python programming language. The script interfaces with the network using a python MQTT module. This module helps us to subscribe to available topics within the broker hosted at the gateway. Once the data is relayed to the script, we wrote functions to filter and sort the data into an organized form it was mapped into tables and columns of the created relational database. The script was hosted on the Linux server and is configured to always be running as a daemon.

B. Database

The script was configured to transfer the data to the MySQL relational database. This database was able to hold a large volume of data. Hence, we opted to utilize it. It also provided reliable speed when executing queries to retrieve the large volume of data. We mapped the JSON payload in Figure 4.10 into rows and columns. The rows were composed of the values coming after every 10 minutes for each ED. The columns were fixed to the payload keys as appears in Figure 4.10.

C. Server

The server in this context is the application server (AP). It hosts all application related services that use the data from the LoRa network. In our case, we used the AP to host the visualization application and the interfacing script. The script is configured to always run in the background as a daemon. We configured Linux crontab jobs on the server to restart all the necessary services if it happens that the server has to reboot. To host the application, the server runs Apache web server. In addition, the MySQL database is installed on the server as well. We also installed and configured the mosquitto broker to be used by the data collection script to communicate with the LoRa NS. The specifications for the server are as follows:

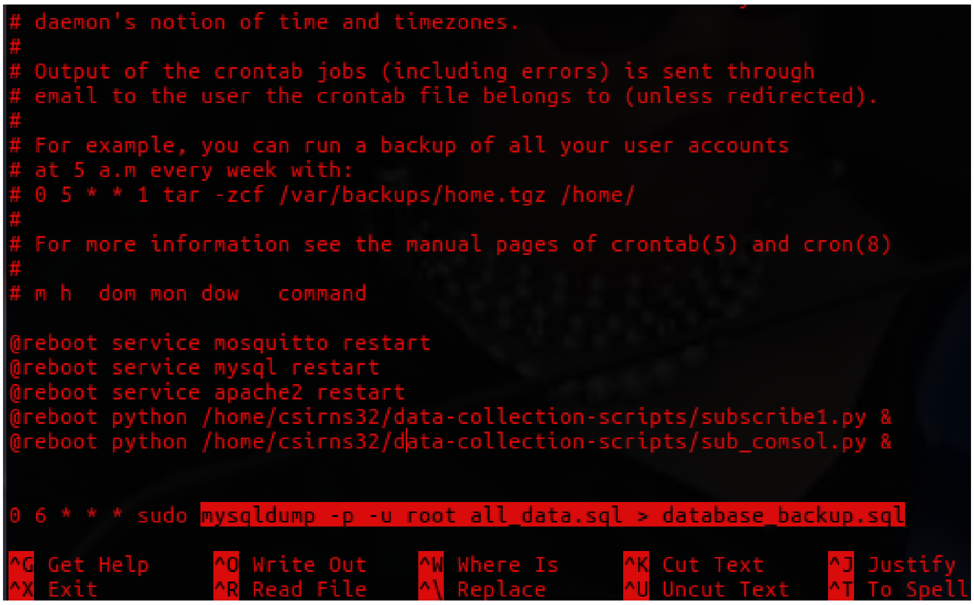

Figure 4.11: Services Restart schedule

OS: Ubuntu 16.04.3 LTS (GNU/Linux 4.4.0-112-generic x86_64)

Disk: 40GB

RAM: 1GB

CPU: 1 Core

D. Backend application

Backend software development consists of a server, a database, and a backend application. The backend application composes of operations to query the database for specific data and prepare it for the frontend for presentation to the user. It can be written in any capable language. We created the application using free and open-source web framework written in python called Django. The framework provides ease of use for development and follows the MVP design pattern, which encourages writing clean code and collaboration ease.

E. Frontend application

Frontend component is the main goal for developing this visualization application in this context because it provided us with graphs that enabled us to analyze the data. For this component, we utilized the template engine that comes with Django framework. Therefore, the backend and frontend are coupled in one application package. Frontend sends requests to the backend to query the needed data and populate the graphs based on the user specification. For the graphs, we utilized a JavaScript graph library called Highcharts [89] which provides great features for visualizing dynamic high volumes of data.

4.12 Test Scenarios

In order to evaluate the performance of LoRa/LoRaWAN, we had to define test scenarios that would guide the evaluation. The defined scenarios are design based on the deployment environment and the network configurations.

4.12.1 Assumptions:

In the context of this research, the following assumptions will hold in our test scenarios:

1) The configurations and parameters discussed above will remain the same.
2) No EDs are going to be relocated whether it is the range or the elevation.
3) The gateway will remain in a fixed position.

Moreover, the following test scenarios are defined:

A. Distance scenario

It describes the range between a single ED and the gateway. In wireless networks when the range is longer, signals tend to lose their strength, because as the signal propagates through space/air it is widely spread. The more the signal spread the more it loses its strength. LoRa offers a greater communication range compared to other LPWANs. In this test scenario, we are going to compare and evaluate the performance of EDs based on their communication range with the gateway.

B. Line-of-Sight scenario

It describes the path between a single ED and the gateway with regard to obstacles. In wireless networks, EDs that have a LOS clear of obstacles tends to perform better than those have non-clear LOS. For this test scenario, we are going to compare and evaluate the performance of those EDs with LOS and those with non-LOS.

C. Obstacles scenario

The obstacle scenario is based more on the physical nature of our campus. This means obstacles would be different for any other environment deployment. In wireless networks, obstacles can affect a wireless signal either positively and negatively. As discussed above obstacles can either reflect the signal in the wrong direction causing interference to other signals or be reflected and attenuated to the destination. Some obstacles absorb the signals causing negative attenuation to the signal. In this test scenario, we were going to analyze the performance effects caused by a variety of obstacles found between the paths' EDs to the gateway.

D. WaterGrid-Sense battery life

In this research, we utilized a sensor node tailor-made by the CSIR specifically for the water management system. This sensor node can be utilized for other industrial applications. Industrial IoT requires sensor nodes that can operate for a longer time without the need to replace the batteries. This also is a design goal for the LoRaWAN protocol. Batteries are expected to last for up to 10 years. However, a protocol alone cannot ensure that lifetime. The design of the node itself is also important to ensure the long life of batteries. In this test scenario, we conducted a battery life test for the WaterGrid-Sense node.

4.13 Chapter Summary

The chapter also described and discussed in details the methodology and methods followed to conduct this research. We described the network architecture and system setup used for this research. The system analysis presented in CHAPTER 2 allowed us to identify the necessary methods needed to conduct this research. The collected data was discussed in detail and the analysis focus was outlined. Finally, test scenarios to be used in the next chapter were provided.

CHAPTER 5

Implementation, Results, and Discussion

5.1 Chapter Outline

This chapter presents the implementation and results analysis performed in this research by following the methods and tools discussed in Chapter 4. It begins with a short introduction, followed by the implementation of the proposed data visualization tool (DVT). Moreover, we present the results of the test scenarios constructed and provide a comprehensive discussion of the results in general.

5.2 Introduction

In order to evaluate the performance of our network system based on the test scenarios constructed in chapter 4, the DVT plays a major role in visualizing the collected data into visuals. The DVT is composed of different components that form a full stack application, the database, the backend and frontend interfaces. The purpose of the DVT is mainly to plot the data into visuals using the defined metrics as parameters. Using the DVT visuals, we were able to analyse the data and evaluate the performance based on the analysis results. The main purpose of the analysis was to evaluate how effective LoRa was when deployed in a harsh environment. To carry out the analysis, we used the defined test scenarios in the previous chapter. We begin by presenting the lab experiment results aimed at studying how long a deployed node can operate without having a solar panel attached to it to harvest energy from external sources. The second part of the results section presents the network results collected from the main network. We divide the results into clusters and analyse them through the scenarios to form a logical flow of the results. Furthermore, we discuss the main findings and draw conclusions from them through the evaluation.

5.3 System Components

The developed data visualization tool is a web-based application as stated in the previous chapter. Therefore, it will operate in almost any modern web browser and be deployed in almost any modern computer operating system (OS). However, the application should be deployed in a web application server; in this research, we utilized the Apache web-server. The web application server configures the domain name mapping and the forwarding of all the requests made to the application. It can also be used for security purposes, for instance, we can configure the ports in which the application can be reached at and filter unwanted requests before the application is reached. Below we discuss the environment setup used in this research to run the application.

A server can either be a computer program or computer hardware used to services other application software or computers called clients. In this research, the data visualization tool is hosted on an application server. In order for the server to serve the visualization tool, there are configurations that are supposed to be brought about on the server and software packages to install. The steps to configure and serve the application are as follows.

In this research, we are using a non-graphical user interface (GUI) server. Therefore, all the configurations and interactions with the server are done through the command-line interface (CLI). In addition, all the software packages installed are server-based packages. Firstly, we are going to install the MySQL database on the server. To install the database, we use the below CLI command:

```
sudo apt-get install mysql-server
```

The installation of the above package allows the package to operate only locally on the machine and external sources are restricted access. However, the database should allow access to other external sources to access the stored data. To allow access to external sources or applications we use the below CLI command:

```
sudo ufw allow mysql
```

The above command will alter the firewall rules to allow remote connections to connect with the database. In this case, applications hosted on different machines can utilize the database. The next command is to enable the MySQL service to start at every boot time of the server.

```
systemctl enable mysql
```

after installing the MySQL server, we need to start the MySQL shell which allows the creation of databases and other functionalities, to start the shell and create a database we use the following commands:

```
mysql –u root –p
```

```
CREATE DATABASE LoRa;
```

From the first command mysql is the name of the shell we want to use, and provided alongside is the username “root” which is the default user and the password by default is blank. The second command is used to create a database name LoRa.

The next setup is to install the application web-server, which will configure the exposure of the application to the external sources and clients. For the proposed web-server, the following steps are for configuring the Apache2 web-server:

To install the software package we used the following command:

```
sudo apt-get install apache2
```

Scripting languages like python produce computer programs that run on the CLI and output on the CLI while running on a server. Therefore, for such programs written in most scripting languages, a standard protocol provided by a framework called common gateway interface (CGI) is used to produce web pages from these languages. Python requires a package called web server gateway interface (WSGI) implemented on top of CGI. Using the below command, we install this package to allow the Apache web-server to serve dynamic pages produced from the python program:

```
Sudo apt-get install libapache2-mod-wsgi
```

After installing the interfacing library, we have to write wsgi file python script that points to the data visualization application as shown in Figure 5.2.

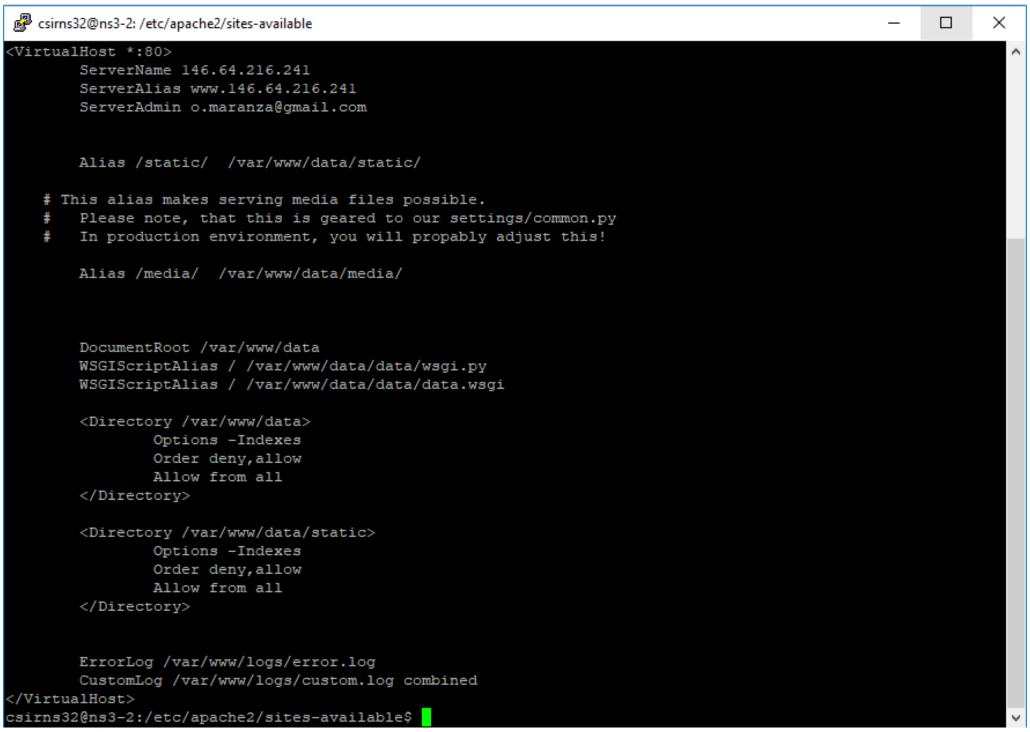

Figure 5.1: Apache Virtual Host Configurations

The next step is to configure the Apache web-server for the application. To be a server for the application we need to create a configuration file in the following path "/etc/apache2/sites-available/" the file name can be named anything but should be of ".conf" format. The configuration code for this file is shown in Figure 5.1. Now to enable the site to be served and restart apache the below commands are used:

a2ensite data-visualization.conf

service apache2 restart

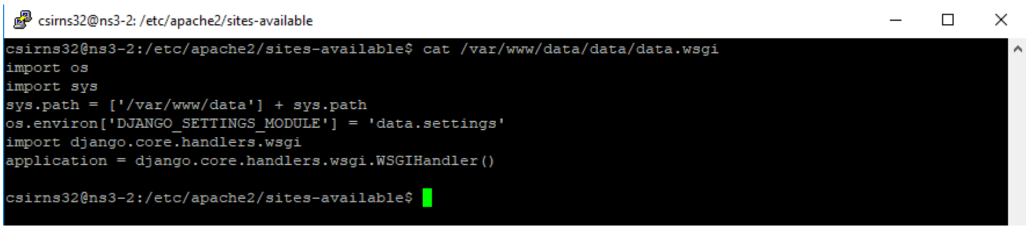

Figure 5.2: WSGI script

Lastly, The Django application developed is then placed in the path where the scripts points to.

5.4 Visualization Tool

In this subsection, the data visualization tool and its implementation are presented. The tool was designed and developed using the methods mentioned in Chapter 4. It is divided into three logical components as shown in Figure 5.3, the data flow and the functionality is according to the order of the components.

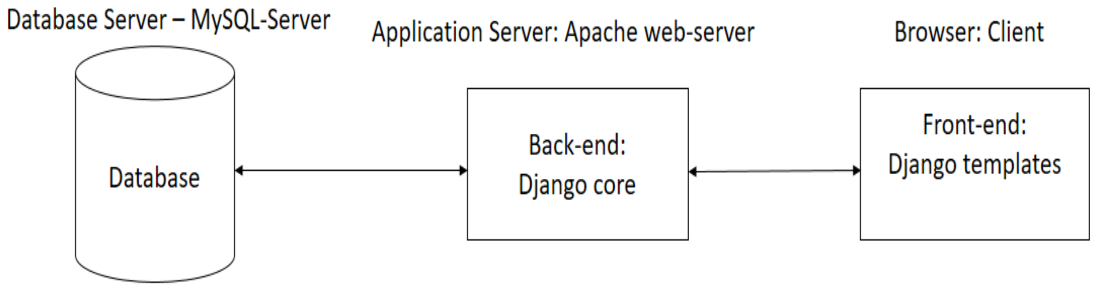

Figure 5.3: DVT Architecture

The tool or system has only one user and the possible interactions with the tool are captured using a use case diagram shown in Figure 5.4. As shown, interactions are through the browser and requests are sent to the backend system where operations are performed. The backend interacts with the database through SQL queries to retrieve data or persist data.

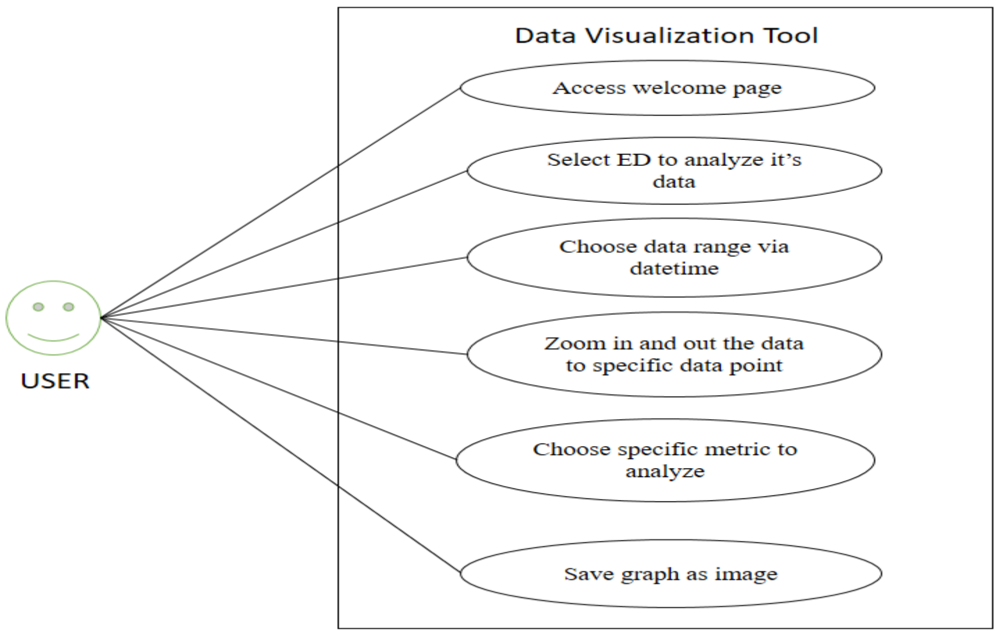

Figure 5.4: Use Case Diagram

Moreover, the sequence diagram in Figure 5.5 presents the underlying operations between all the system components including the user.

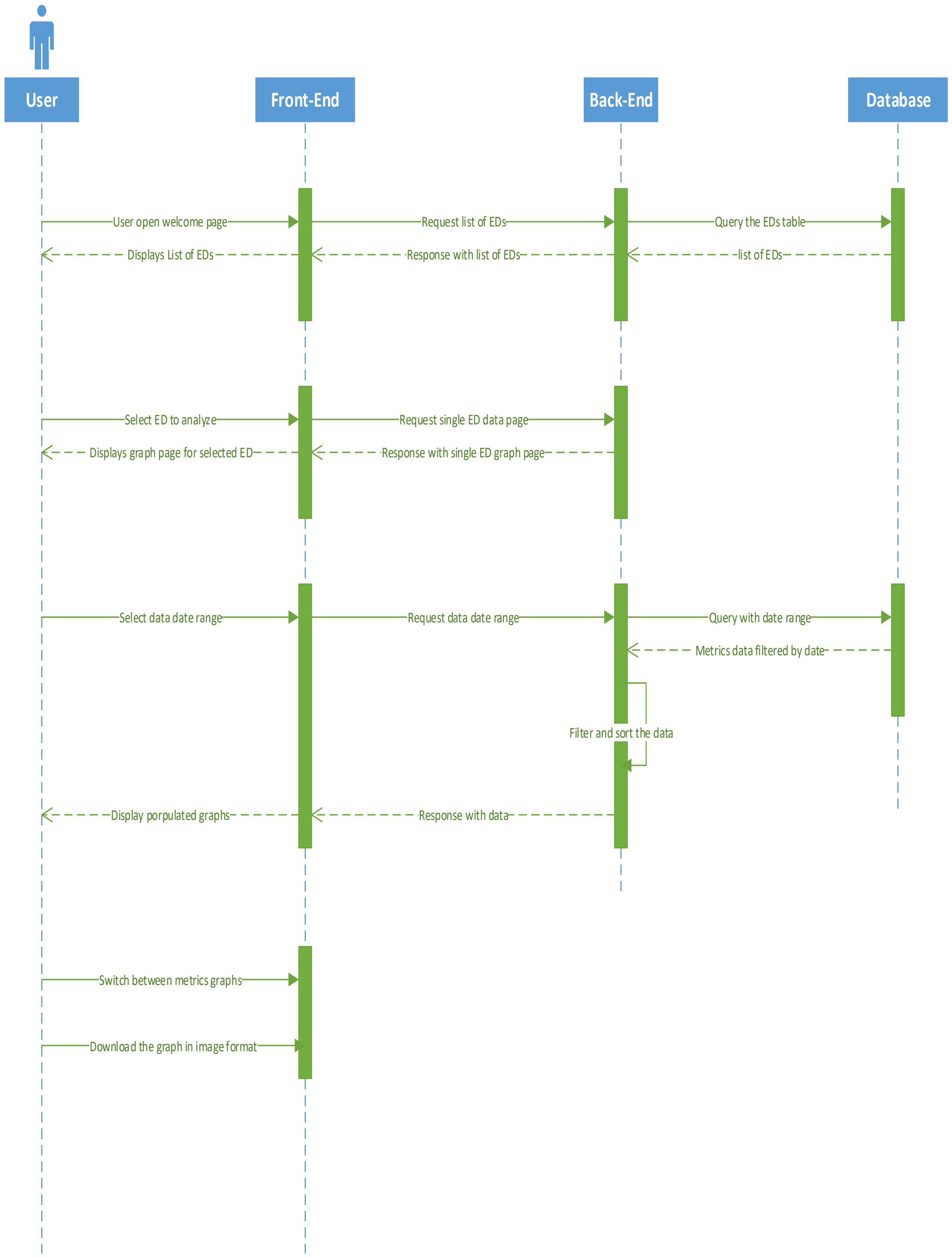

Figure 5.5: Sequence Diagram

Based on the functionalities shown in Figure 5.4, the components of the tool that enables the efficient utilization of functionalities are discussed:

A. *Home page:* The home page as shown in Figure 5.6 is a basic web page that lists all the EDs with their statuses whether they are online or offline. The status feature plays an important role in determining which devices are currently operating and transmitting. When a device is offline, it can be attended to and reconnected to the network. From this page, the user can select which node they want to analyze by clicking on the analyze button.

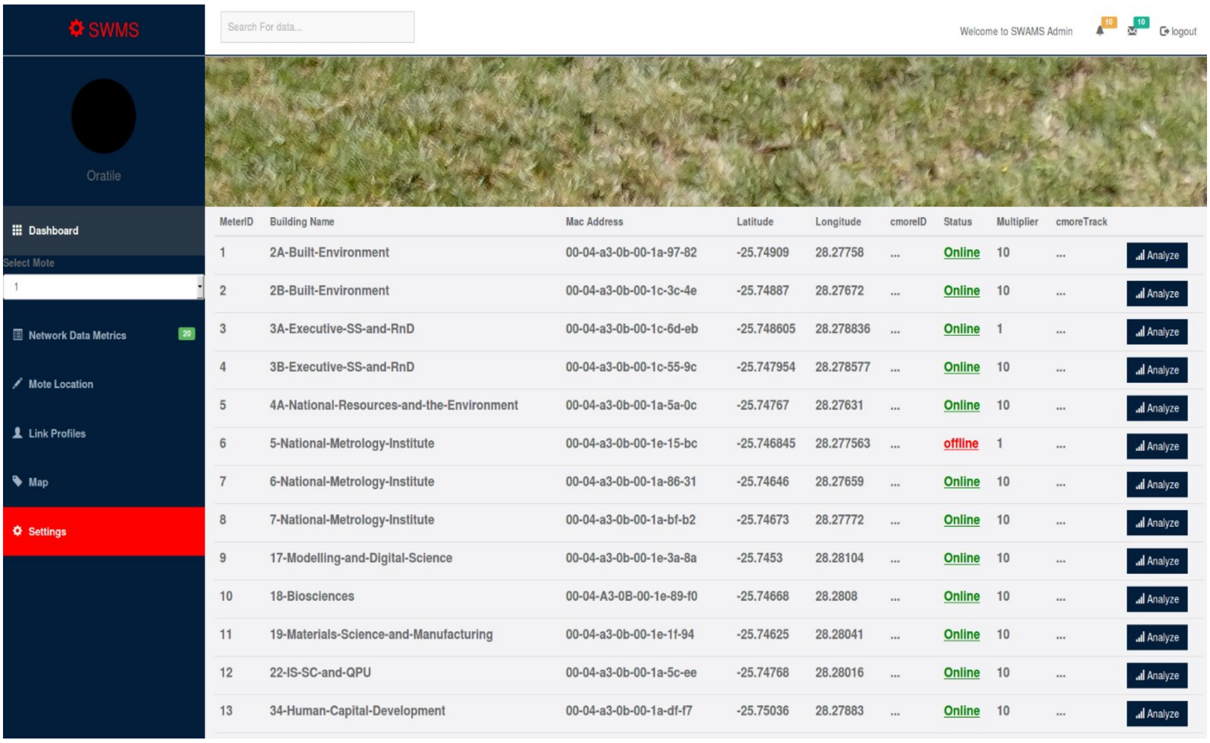

Figure 5.6: DVT Home page

B. *Analysis page:* Within the home page, the graph page can be reached by clicking its button as is shown in Figure 5.7. It contains more information about the node, its location point, and operational status. To access this information, a user can query the data using the Datetime range period. Once the request is sent, the graph it populated with data points as shown in Figure 5.8 and the tool under the graph can be used to zoom in the graph to any of the data points of interest and dragging a certain area width on the graphs to focus on that particular area. Moreover, the user can use the tabs shown in Figure 5.9 to switch between performance metrics. To download the graphs for offline use the user can click on the three bars appearing on the top right of the graph shown in Figure 5.8.

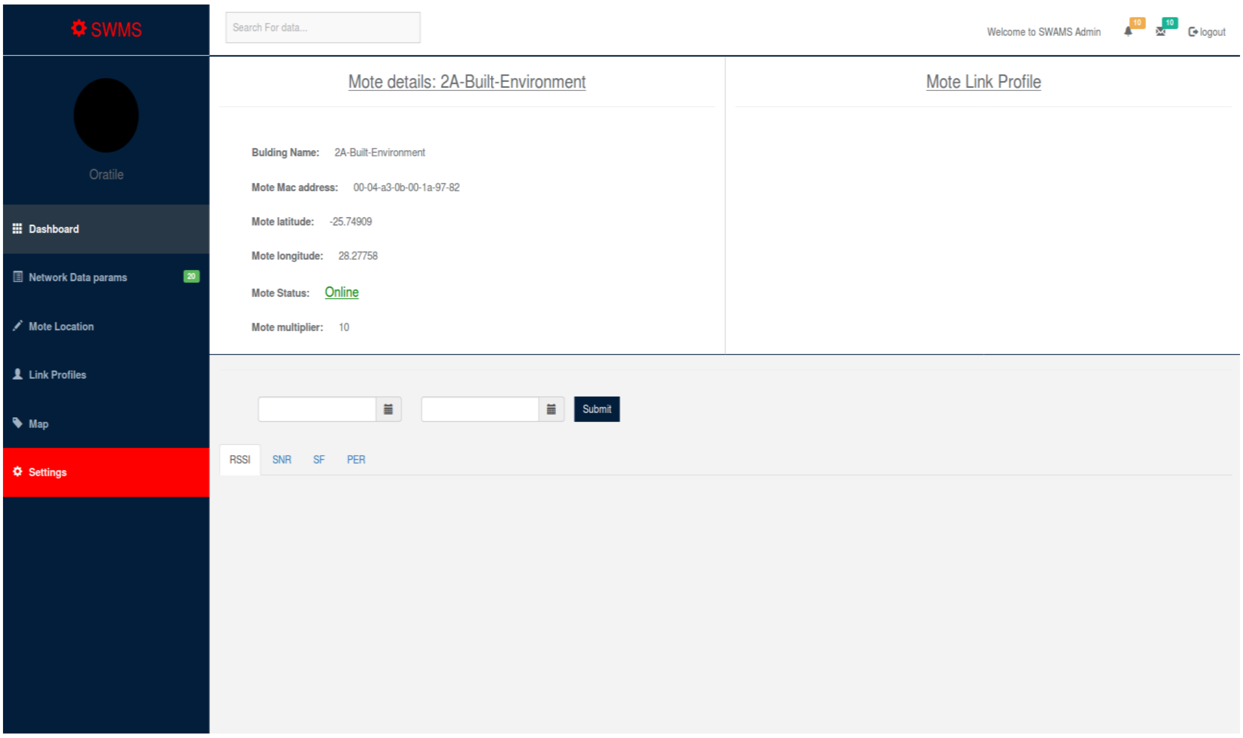

Figure 5.7: DVT Graph Page

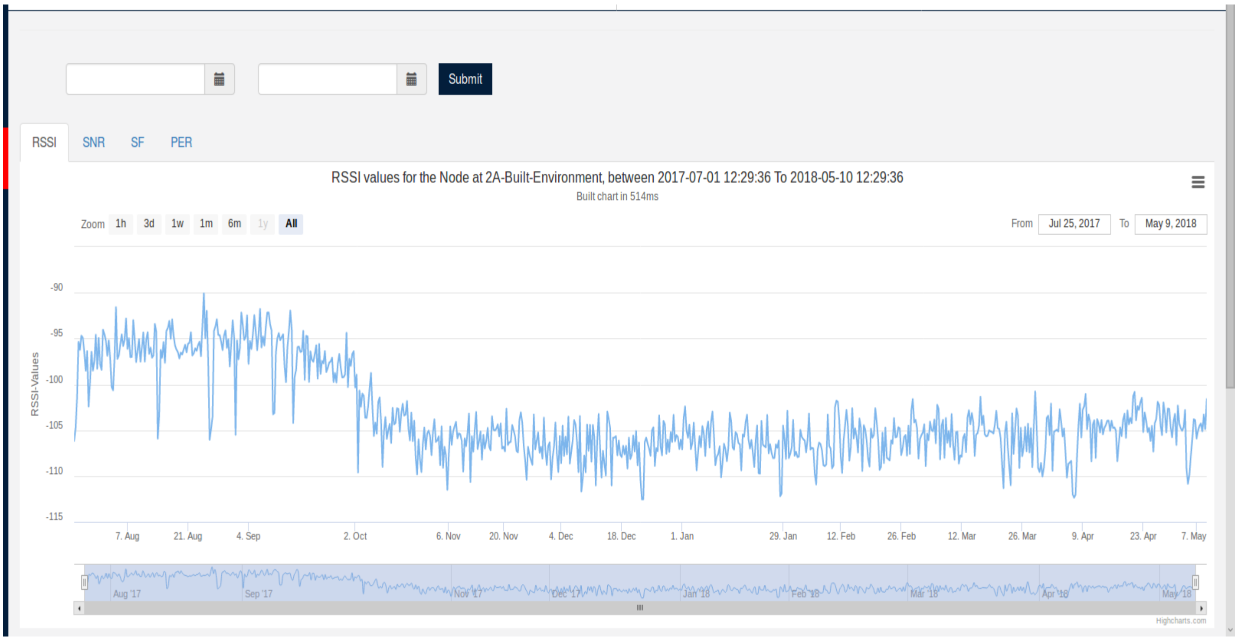

Figure 5.8: DVT Graph

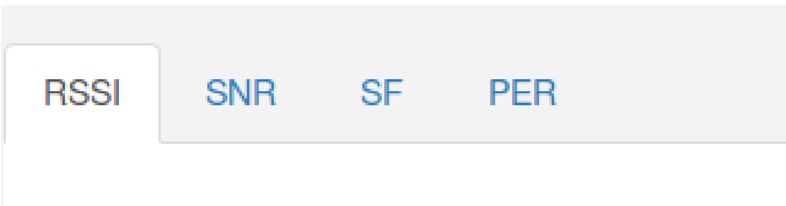

Figure 5.9: DVT Metric Selection

5.5 Results and Analysis

The importance of our performance analysis and evaluation was to test the effectiveness of LoRa as a communication link for our network, considering the harsh environment the network operated in. As mentioned, the data visuals were generated by the DVT the collected network data. We strictly followed the methods outlined in CHAPTER 4. First, we focused on the node experiment results, which involved observing the power consumption rate of the node while in operation and secondly, observing how the network behavior corresponds with the load on the device. In all, the study was conducted for two days with the node placed indoors, hence the study of indoor (node) to the outdoor (gateway) deployment scenario was presented. The second part of the results was based on the defined test scenarios to determine the effectiveness of the network based on the performance evaluation with regard to the environment of deployment.

5.5.1 Lab Experiment Results

This subsection was based on the study for WaterGrid-sense presented in chapter 3. The laboratory investigation was conducted over two days. The objectives were to study the power consumption of the node and to study its load behavior when in the network operation.

5.5.1.1 Power Consumption

The aim of this part of the study was to observe and study how long the battery of the device would last without an external energy (solar) source. This was to study its behaviour during the initial communication routine when first joining the network, in relation to battery usage. The study presented an indoor to an outdoor scenario with the node placed indoors and gateway outdoors, here also the data was logged over two days.

A. ***Experimental Set-up***

In this investigation, we assumed WaterGrid-Sense to conserve energy out of the box since its design approach was based on system-on-chip (SoC) [65] concept. The goal was to evaluate the lifetime of the sensor node operating only on a battery. The experiment was conducted to observe the power consumption of WaterGrid-Sense while in its normal operation over time. The sensor node was programmed, configured, and connected to the network. The battery voltage was 3.7 V, capacity of 1000 mAh, and with a maximum charge of 4.2V at 500 mA was used to power the node. Moreover, in order to measure both current and voltage flowing between the battery and the node, a dummy resistor of 1.4 ohms was attached between the battery and the node as shown in Figure 5.10. Moreover, attached to the node was the 868 MHz antenna to connect to the LoRa network Gateway and the experimental setup was left running for some time while the mote was in normal operation.

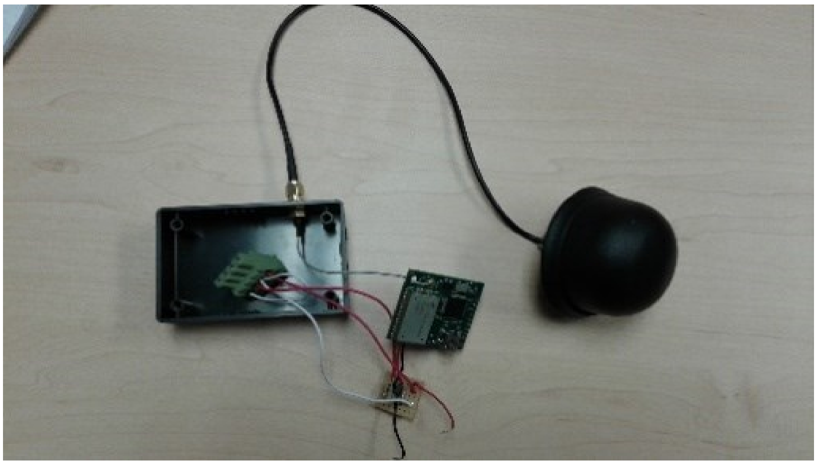

Figure 5.10: Dummy resistor and antenna attached to the node

Figure 5.11: Experiment setup

Figure 5.11 shows the whole setup, where a Delphin Expert Key 100L[90] data logger was used for logging data in mV for both the battery and the load created by the dummy resistor. The data logger was configured to record 10 samples per second and then display the corresponding node operation with respect to time. From the logged data, we have load voltage (V_L) in mV, which is the voltage across the dummy resistor, and battery voltage (V_L) in mV, which is the voltage across the battery. Equation (5) calculates the current flowing through from the battery, Equation (6) computes the voltage through the node, and finally, the power consumed by the node can be calculated with Equation (7):

$$I_L = \frac{V_L}{R} \quad (5)$$

$$V_N = V_B + V_L \quad (6)$$

$$P = I^2 R \quad (7)$$

$$V_B = V_L + V_N \quad (8)$$

where I_L is current from the battery through the load to the circuit, V_L is the voltage across the dummy resistor, R is the 1.4 ohms' dummy resistor, V_N is voltage at the sensor node, V_B is battery voltage, using equation (8) equals to battery voltage, and finally, P represents the power obtained through equation (7). The node under test is configured together with other nodes connected to the network, to transmit data after every 10 minutes.

B. Results

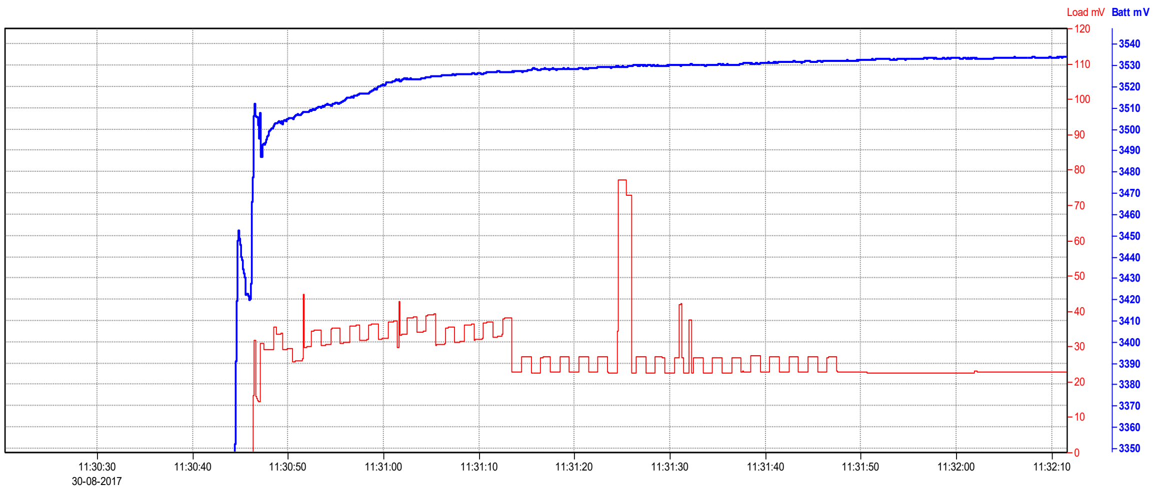

Figure 5.12: LoRa Join Operation

Figure 5.12 shows the initial operation when the node performs join operation with the LoRa network server. As shown on the graph, multiple beacons are sent to the server and after the join operation, the sensor node enters the active state for some time until it enters sleep and transmission mode. Moreover, Figure 5.13 shows the operation of the node against time. The blue line represents the battery voltage usage and the red line is the different states of the sensor node over time. As expected, the voltage dropped over time from 3.770V to about 3.703V over a period of 1 day. The sensor node has three different operational states as seen in Figure 5.13, which are sleep state, sensor reading state and radio transmission state:

1) Sleep state uses 0.1 mV, where no operation is active on the device and the active state divided into two states which are
2) Sensor reading state which uses about 23mV and
3) Radio transmission state, which uses 73mV.

More voltage was drawn from the battery as the sensor node transmitted the data to the gateway. However, the advantage is that the transmission only occurs after every 10 minutes, contributing more to energy conservation.

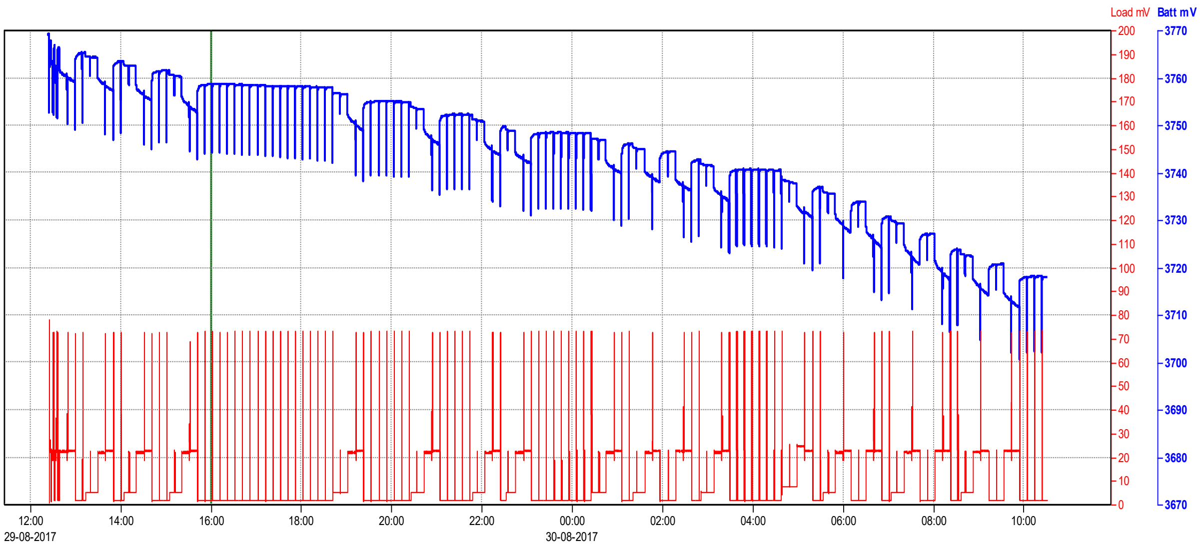

Figure 5.13: Node Operation over Time

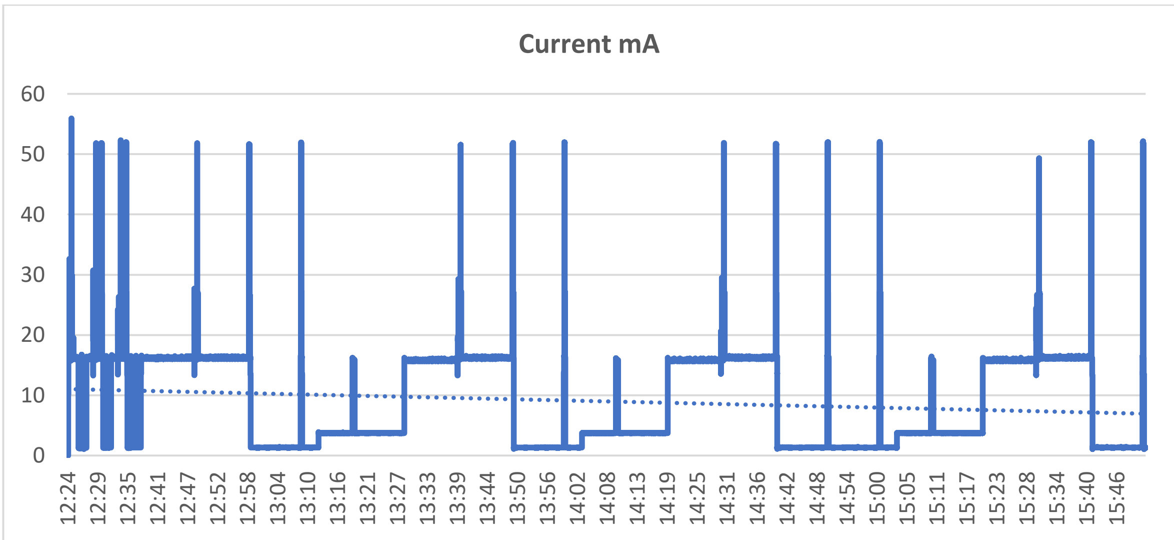

Figure 5.14: Current With Respect To Time

To further verify and perform critical power consumption studies the sensor node under observation was monitored from the server side as it was on its operational states. We found out that the sensor node would sometimes initiate the linking procedure with the network as time goes on and this was caused by weak received signal strength from the gateway side. The node has the capability to go from the sleep state to radio transmission state and transmit data successfully as shown in Figure 5.13. From around 15:40 pm to 18:40 pm the sensor node was operating from the sleep state and radio transmission state, which resulted in constant voltage as seen from the graph. This constitutes a lot of energy conservation as well. The power consumption corresponds accordingly with the states of the sensor node, during transmission; the power consumed by the sensor node was 190 mW and sensing states or idle state the node is 52 mW as well as 0.1 mW when on sleep state as shown in Figure 5.15. In general, the battery consumes about 0.067 V per day, which resulted in the battery lasting about 2 months. However, as discussed in Chapter 3, an energy harvesting technique was employed via a solar panel to charge the battery hence, extending the lifetime of each sensor node on the network. Furthermore, to obtain the cut-off point required to drive sensor node voltage we powered the sensor node with a voltage supplier and reduced the voltage accordingly, and the resulted voltage cut-off was 3.2V.

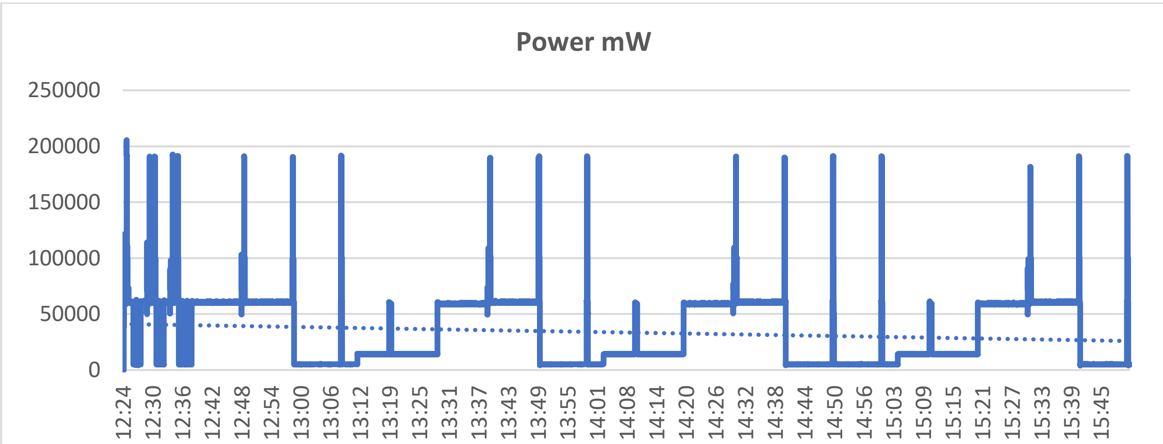

Figure 5.15: Power Consumption With Respect To Time

Table 5.1: Average power consumption results (Test Node)

State	**Tx**	**Idle/reading**	**Sleep**
voltage	73mV	23mV	0.1mV
current	0.52mA	0.16mA	0.1mA
Power	190mW	52mW	0.1mW

5.5.1.2 Communications Link

WaterGrid-Sense is a LoRa based industrial sensor node, offering the flexibility to be deployed for different monitoring and actuating application with lower data rates and long-range communication. In the above experimental setup, we tracked the network data from the server side as it was transmitted from the test sensor node shown in Figure 5.10. The objective was to observe how LoRa performs when the end-device is deployed indoors communicating with the gateway located outdoors.

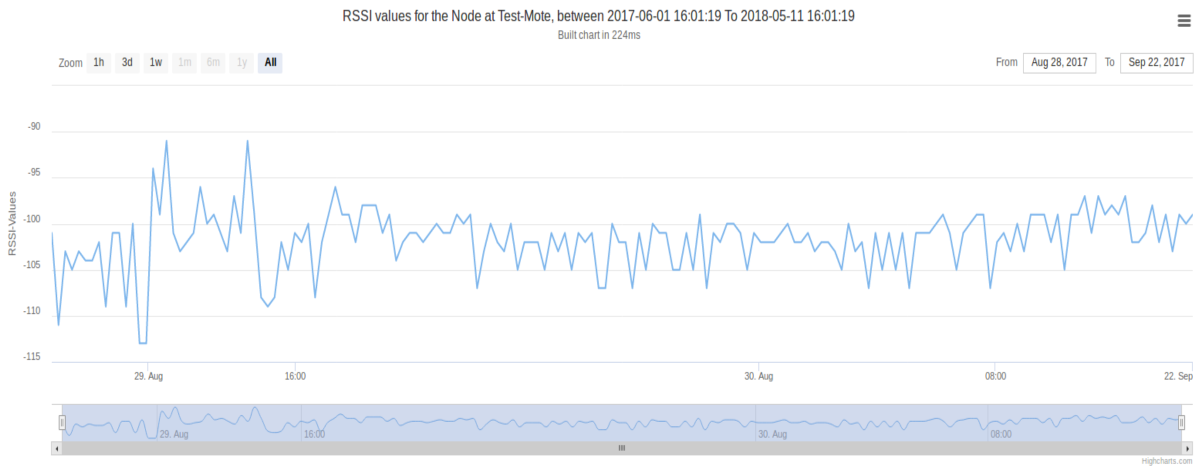

Figure 5.16: Test node RSSI over time

The results presented in Figure 5.16 show received signal strength indicator (RSSI) measured in dBm, with the best value of -91 dBm and worst value of -119 dBm. RSSI indicated the received signal power level after a combination of all possible loss along the propagation. The higher the RSSI value the stronger the received signal strength and LoRa can detect signals up to -134 dBm below the noise floor. This makes it the most robust LPWAN wireless communication technology. Accordingly, Figure 5.17 presents LoRa signal to noise ratio (SNR) which ranged between 9 dB down to -3.1 dB throughout the whole study.

Table 5.2: Average Communication Performance (Test node)

Node	RSSI (dBm)	SNR (dB)	SF	PDR (%)	PER (%)
Test node	-101.69	4.7	12	99.42	0.58

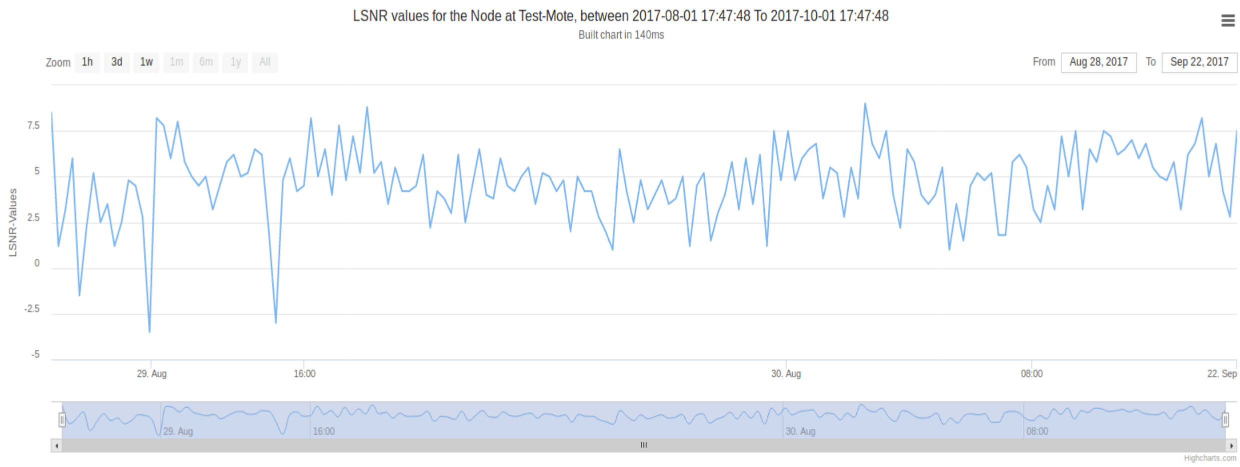

Figure 5.17: Test node SNR values over time

5.5.2 Network Results

This section presents the results for the network. The aim for these test scenarios was to determine the impact of distance, environmental factors such as physical obstacles, and line of sights for the nodes on the network. The results were generated by the DVT in a form of graphs presenting the evaluation metrics. The results were classified according to the test scenarios for the evaluation objective presented by each scenario. Table 5.3 shows the average summary of the results collected.

Table 5.3: Summary of average results for all the Nodes

id	Mote	RSSI	SNR	SF	Sequence	PDR	PER	classification	distance
1	3A-Executive-SS-and-Ri	-92.29	7.23	7.91	1732	97.57	2.43	duster-1	0.59
2	2A-Built-Environment	-103.89	3.57	9	450	97	3	duster-1	0.59
3	2B-Built-Environment	-106.47	2.82	9.57	1183	97.06	2.94	duster-1	0.66
4	3B-Executive-SS-and-Ri	-106.75	2.19	9.87	1254	97.65	2.35	duster-1	0.67
5	4A-National-Resources-	-104	3.47	9.66	664	97.68	2.32	duster-1	0.79
6	5-National-Metrology-I	-111.42	-2.53	12	96	97.88	2.12	duster-1	0.82
7	6-National-Metrology-I	-110.42	-1.15	10.8	997	97.24	2.76	duster-1	0.9
8	7-National-Metrology-I	-105.02	2.95	9.67	678	97.25	2.75	duster-1	0.83
9	17-Modelling-and-Digit	-107.83	1.11	11.72	236	98.85	1.15	duster-1	0.94
10	18-Biosciences	-104.35	3.41	11.03	538	98.74	1.26	duster-1	0.79
11	19-Materials-Science-ai	-87.71	7.95	9.72	289	99.55	0.45	duster-2	0.84
12	22-IS-SC-and-QPU	-98.15	6.12	8.35	489	98	2	duster-2	0.68
13	34-Human-Capital-Deve	-102.86	4.17	9.26	733	97.79	2.21	duster-2	0.41
14	39-International-Conve	-108.29	0.19	11.46	319	98.65	1.35	duster-2	0.2
15	41-Defence-Peace-Safe	-98.07	5.87	11.12	323	99.49	0.51	duster-2	0.2
16	42-Human-Capital-Deve	-96.39	6.03	12	681	99.54	0.46	duster-2	0.3
17	46F-Laser-Center	-106.44	2	11.29	456	99.08	0.92	duster-2	0.58
18	50-Knowledge-Commoi	-108.21	0.64	10.35	712	97.65	2.35	duster-2	1.03
19	36-SS-(Facilities Manag	-102.23	4.45	11.19	339	99.42	0.58	duster-2	0.22
20	23-SII-Unit-ECOD-and-S	-98.6	6.22	8.41	758	97.77	2.23	duster-2	0.62
21	15-Materials-Science-ai	-108.42	1	10.38	701	97.37	2.63	duster-2	1.09
22	14D-Materials-Science-	-100.15	4.7	10.83	458	94.9	5.1	duster-2	1.23
23	13-Defence-Peace-Safe	-100.3	5.39	8.57	547	97.6	2.4	duster-2	1.27
24	11-Defence-Peace-Safe	-100.68	5.45	8.67	885	97.55	2.45	duster-2	1.16
25	10-CAS-and-SII-Unit	-97.95	6.47	8.37	784	97.54	2.46	duster-2	1.23
26	Test-Mote	-101.69	4.7	12	37	99.42	0.58	duster-2	NULL
27	8 - National Metrology I	-109.44	0.03	11.88	89	98.11	1.89	duster-3	0.98
28	9 - Shared Services (ICT	-101.89	4.41	10.17	475	99.02	0.98	duster-3	1.06
29	37 - Medical Centre	-95.02	6.53	12	3	99.02	0.98	duster-3	0.18
30	20 - Biosciences	-86.79	6.97	12	3	98.45	1.55	duster-3	0.75
31	16A - Defence, Peace, S	-108.67	0.83	11.53	218	98.52	1.48	duster-3	0.99
32	12A - Defence, Peace, S	-89.03	7.76	10.22	72	99.62	0.39	duster-3	1.12
33	14B - Materials Science	-108.73	0.81	11.57	251	98	2	NULL	1.29

Criteria:

- The RSSI is evaluated using the receiver sensitivity value, which was found to be -131 dBm for our network.
- The SNR values desired are positive values.
- Lower SF values indicate a good communication link.
- The node at building-(number) – refers to a node deployed at a certain building water meter around the campus, full building names are shown in graphs however in the context we refer to them using their numbers.
- Worst performance/performing node - means the lowest value for a certain metric based on performance.
- Good performance/performing node - means the highest value for a certain metric based on performance.
- Furthest node/long range node (ED) - means the node with the largest communication range to the gateway.
- Closest node/short range node (ED) – means the node with the shortest communication range to the gateway.

5.5.2.1 Pre-Analysis Using Distance Scenario

Impact of placement distance

As discussed in the scenario description, the goal of this study was to determine the impact of distance between the nodes and the gateway. To achieve this, we used the defined metrics to evaluate the performance of the deployed devices based on their location (range) of deployment with regard to the gateway. To carry out the evaluation, we commenced by taking a single closest and the furthest node in relation to the gateway as depicted in Figure 5.18. As shown in Table 5.3 the distance column, the farthest node is at building-14B and the closest node is at building-3. As shown in Table 5.3, it is evident that the node at building-37 yields better results compared to the node at building-14B.

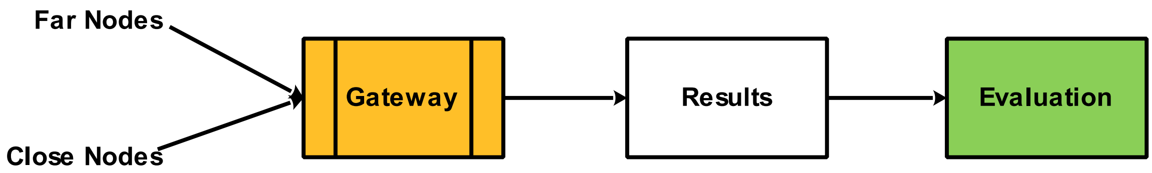

Figure 5.18: Pre-Analysis with the furthest node and closest node

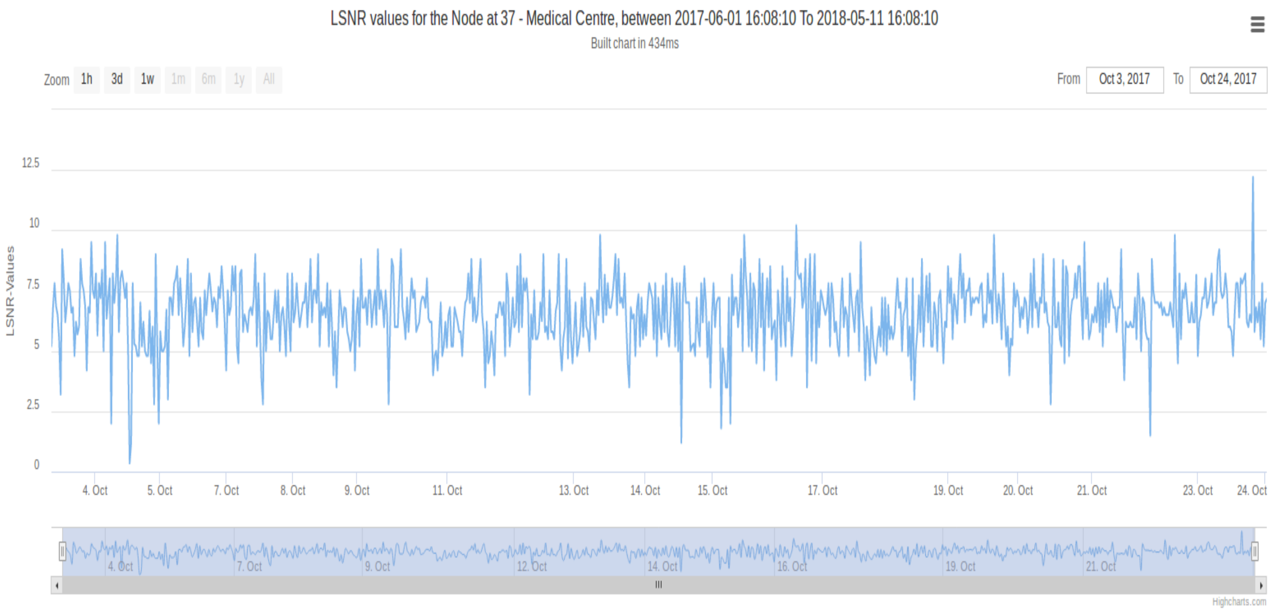

Figure 5.19: RSSI for Building-37

The RSSI value for the closest node was -95.02 dBm and that of the furthest node was -108.73 dBm, considering the definition of RSSI these results are valid, RSSI for short-range tend to be higher than those of long-range distances. This is because the signal loses its strength as it propagates through space and obstacles. Looking at the map shown in Figure 4.3 we can see that the signal from the node at building-14B has to travel a bit longer while penetrating obstacles such as buildings and vegetation and other network signals present on campus.

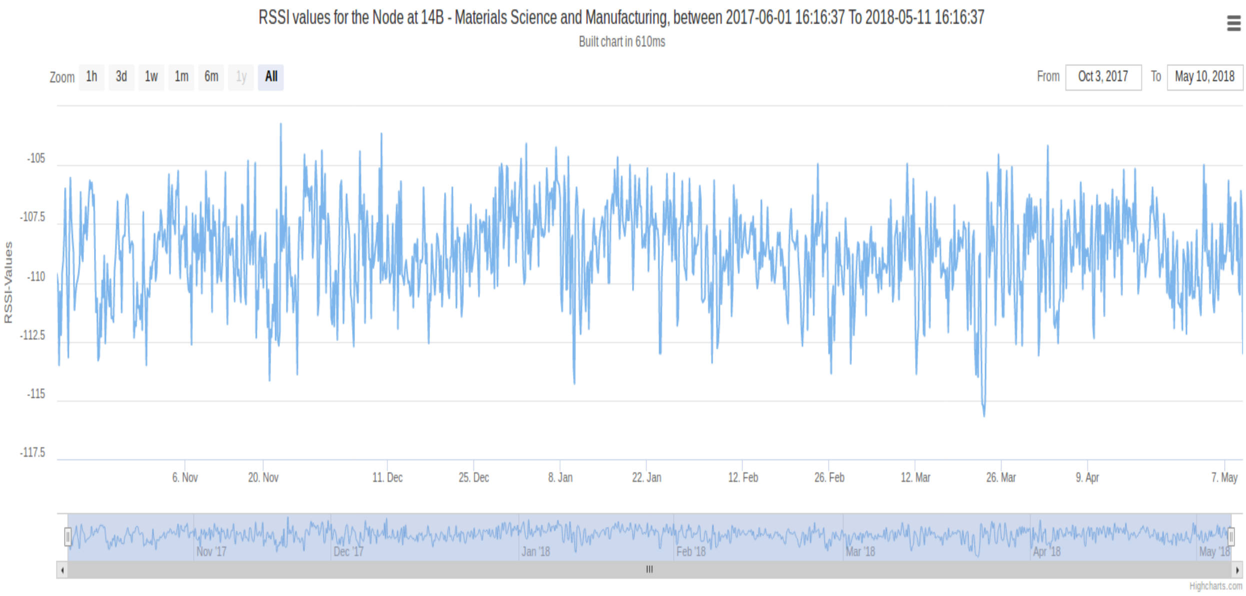

Figure 5.20: RSSI for Building-14B

Moreover, with the graphs shown in Figure 5.19 and Figure 5.20 respectively, there is consistent wave behaviour of RSSI for the shortest range node and a clear variant of wave behavior for the longest range node. Both graphs have more peaks on the lower side than on the upper side this signifies the negative reaction of the network when it finds difficulties for the link and the cause might be interferences caused by external factors. By having a closer look at the results in Table 5.3, it is clear that the longest range ED even reached the value -131 dBm which seems to be the maximum sensitivity value for our network. The shortest range ED RSSI values ranged from -85 dBm to -114 dBm, which is a difference of -29 dBm and the longest range ED RSSI values ranged from -78 dBm to -131 dBm, which gives the difference of -53 dBm. The results justified what appear on the RSSI graphs for these two EDs and thus, it is evident that distance does have an impact on the RSSI.

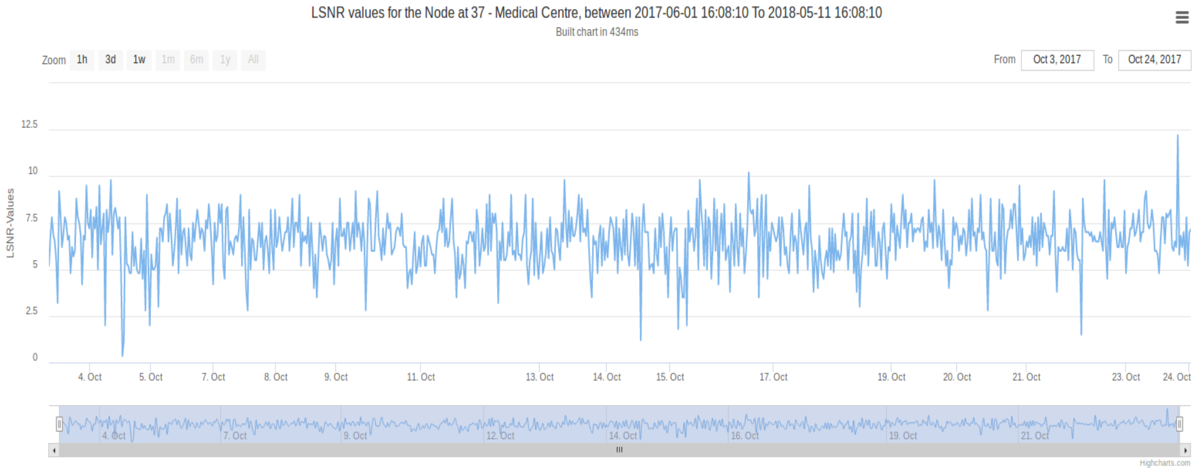

Figure 5.21: SNR for Building-37

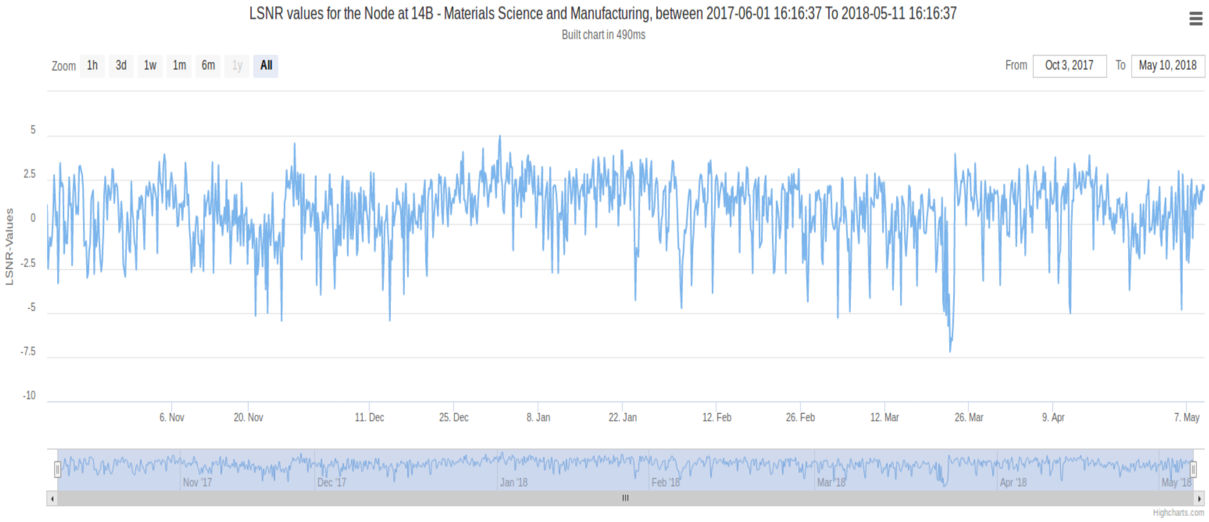

Figure 5.22: SNR for Building-14B

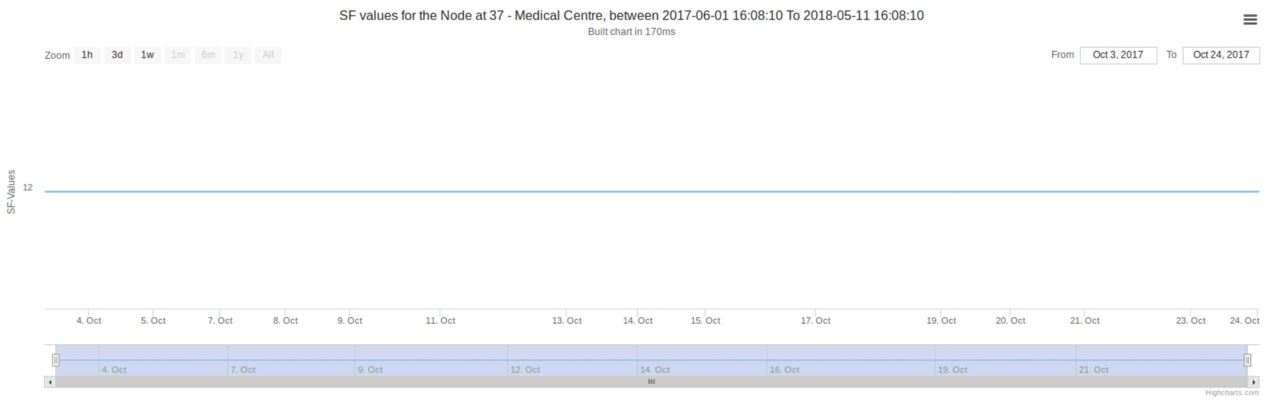

Figure 5.23: SF for Building-37

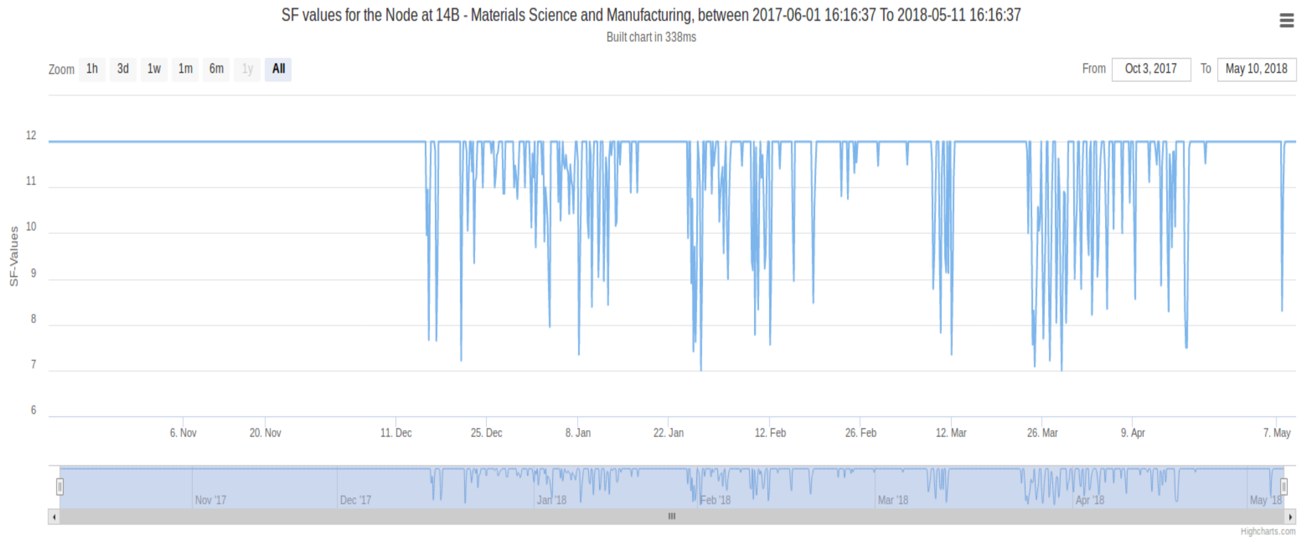

Figure 5.24: SF for Building-14B

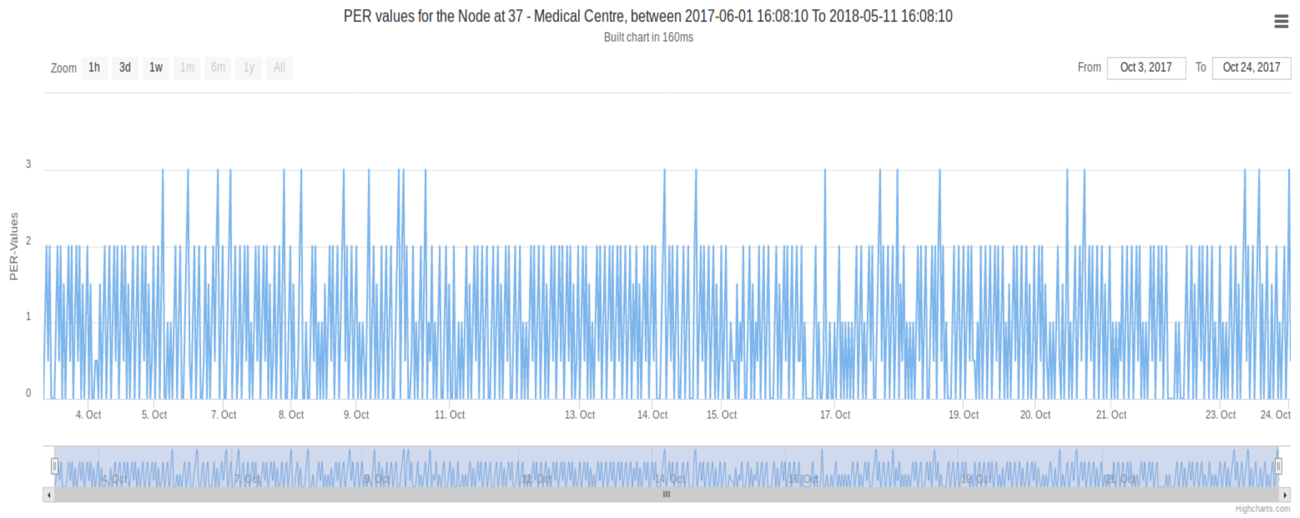

Figure 5.25: Sequence values for Building-37

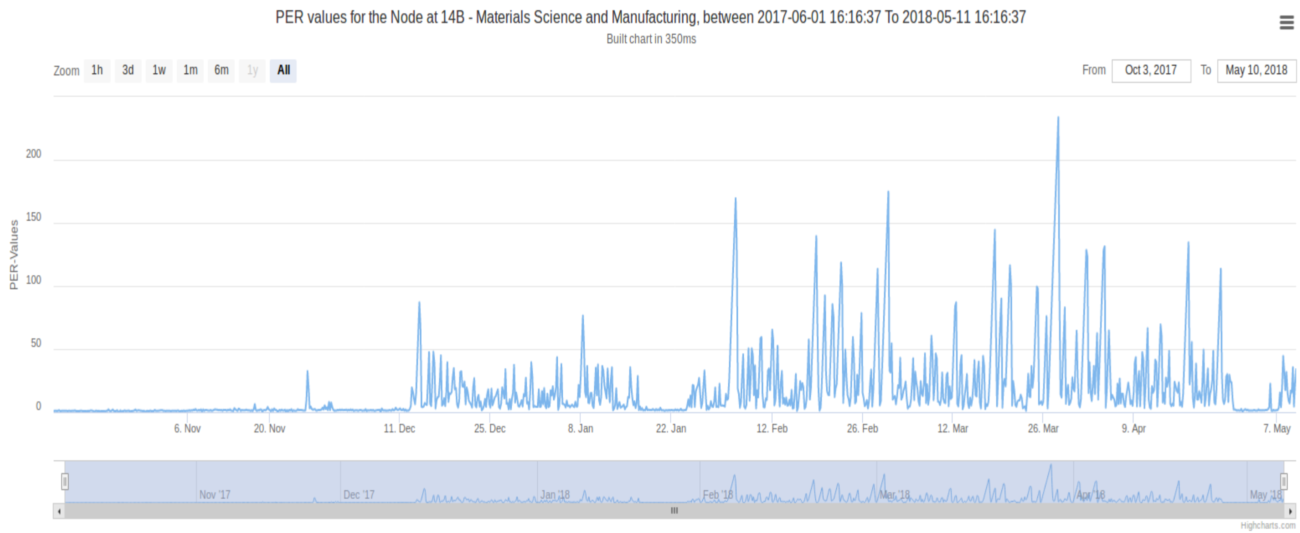

Figure 5.26: Sequence values for Building-14B

Impact of physical obstacles

A closely related metric to RSSI is the SNR. As the signal propagates in space it is exposed to external noise, signal noise can be anything and can be generated by anything the signal encounters while in transmission. As described, this network is deployed in a very harsh environment. The signals are exposed to external noise caused by for example other networks operating around campus, industrial work happening around campus, machinery, objects etc. desired SNR is higher values, lower values present a signal loss due to noise present in the signal. This problem can cause packet errors and packets loss for the network links. Now evaluating the two ED's with this metric, the short-range node yielded an average SNR value of 6.53 dB and the long-range node yielded 0.81 dB. The difference between these values is a significant one, to see the cause of these results we will use the map in Figure 4.3. We can see that the long-range node is exposed to more external noise than the short-range node because of the distance. The short range node went through a single building and vegetation to reach the gateway while the long-range node went through multiple buildings. We consider buildings because they tend to attenuate signals more than vegetation does, moreover, both node links are exposed to vegetation and operating networks around the campus. We will later evaluate nodes that are situated in an open space concerning LOS to the gateway to evaluate the performance results they produce as compared to those behind buildings.

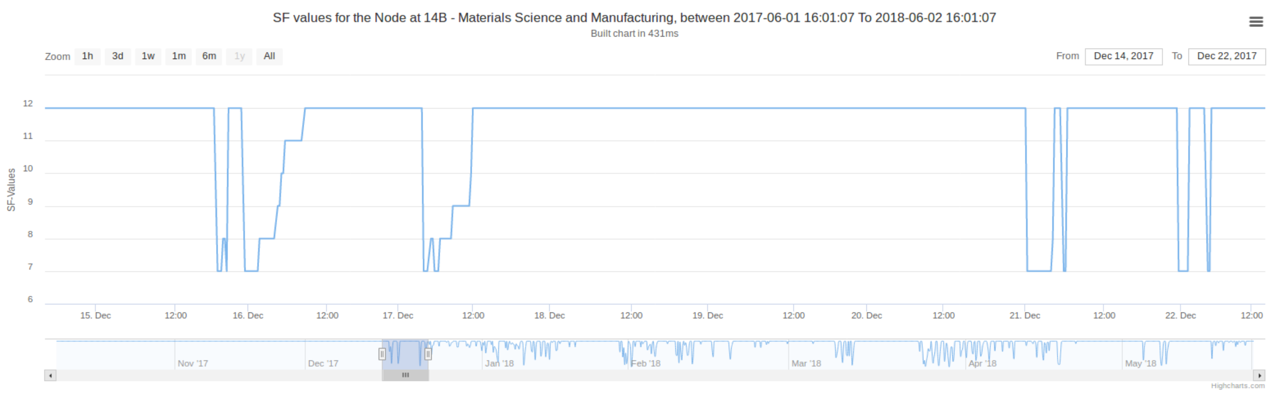

Figure 5.27: ADR effects on the SF for Building-14B

Network configurations impact

Both RSSI and SNR are related in showing the strength of the signal at the receiver side, and they are generally influenced by the network parameter settings before the environmental factors. If the network is incorrectly planned and deployed, poor results should be expected regarding SNR and RSSI. However, the uniqueness of LoRa lies in the use of the spreading factor (SF), which is also a network parameter setting, for LoRaWAN networks. By evaluating the SF, the signal performance will enable us to justify any other results. The SF forms part of the data rate used to transmit the packets and the ADR feature for LoRaWAN allows the network server to adjust data rates for nodes depending on their link profile during the time of transmission.

The short range node used a constant SF value of 12 throughout its lifetime as shown in Figure 5.23. The long-range node also yields an average SF value of 11.57 throughout its lifetime with 12 being the mode value. Moreover, as per the graph in Figure 5.24, ADR changes took effect after a period of two and half months, changing from 12 to 7 straight away, and thereafter we observed similar repeating patterns of ADR on the spreading factor alternating through other SF values as shown in Figure 5.27.

LoRa is said to have the ability to connect a link up to 15 km away. However, in our scenario the maximum distance was 1.29 km, it is not surprising for the node to have communicated using SF 7 because if the link allows, the ADR will choose the best efficient settings to transmit. The ADR selects the lowest SF mostly in cases where there is less interference in the link, for instance when there is clear LOS. Thus, this explains why the short range node used SF 12 for its entire lifetime although it was the closest to the gateway. This was because the node is behind a building positioned on a water pipe attached through the building's wall. The building blocked the link completely in a close-range manner.

Network reliability

Another performance measure used in this work is the sequence number. The sequence number denotes the order of packets sent in a sequential form. The values of the sequence number start from zero with increments of one accordingly up to a point where it resets back to zero. The reset does not affect the transmissions, however, they show when the device changes data rate, channels, etc. We also use the sequence number to find the PER and PDR through missing values and present values. The more the node resets its sequence number, the poorer its performance will be and the more it reaches higher sequence number values the better the performance. The maximum sequence value the short-range node could reach was three throughout its lifetime and the node was alternating in patterns as shown in Figure 5.25. This is a lower value and shows that the node was struggling throughout because of the building blocking the link.

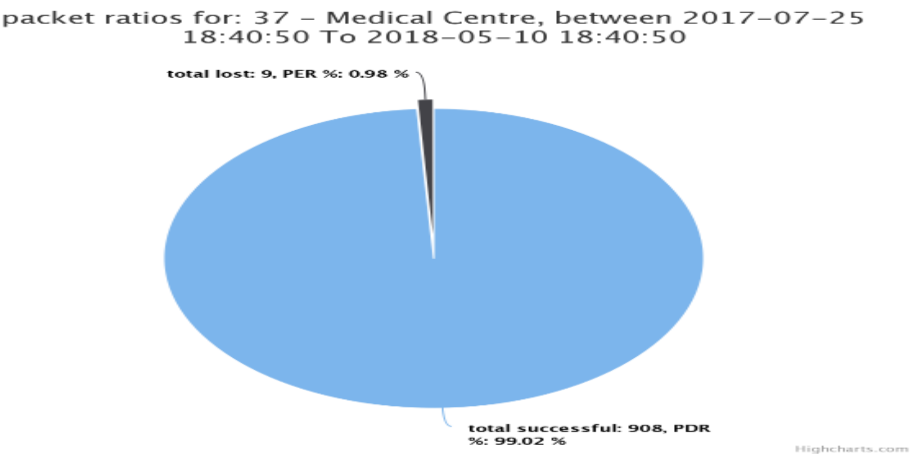

Figure 5.28: PDR & PER Building-37

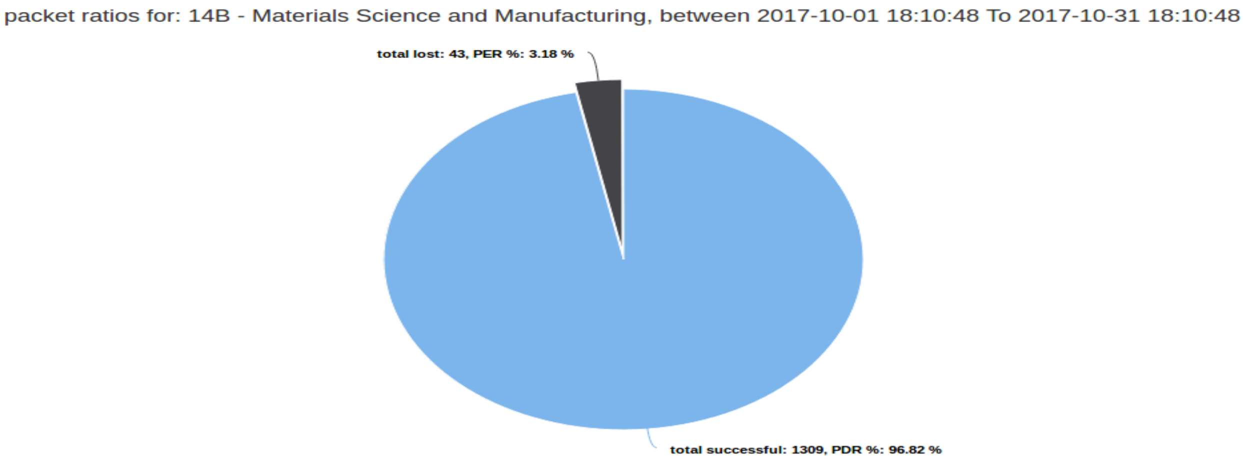

Figure 5.29: PDR & PER Building-14B

However, the increased LoRa sensitivity while using higher spreading factors yields good PDR as shown in Figure 5.28, the node achieved 99.02% PDR and the PER was 0.98%, the total packets sent were 1007 and 908 were successful and only 9 were lost. These results are because of the Forward Error Correction (FEC) Code Rate (CR). This additional coding rate offers redundancy to detect errors and correct them.

The analysis was done for both nodes for the duration of their lifetimes on the network. They were deployed on the same day 03 October 2017, and the short-range node operated for one month while the long-range node was still operating during the time of this analysis (June 2018). Figure 5.23 and Figure 5.26 shows a similar pattern compared to the short-range node results, both nodes used SF 12 and alternated between same sequence values during their first month on the network. However, the short-range node only operated for a month. The subsequent analysis should help in investigating why the device was not able to operate for a longer time.

5.5.2.2 Distance Scenarios Impacts

To carry out analysis of a collection of nodes according to their locations, we grouped them into three clusters as shown in Table 5.3, on the distance scenario column. There is Cluster-3, which consists of nodes under a distance of 500 meters, Cluster-2 nodes under 1km and Cluster-1 nodes over 1km. The framework is shown in Figure 5.30. The objective of this analysis was to evaluate and compare the performance of the nodes based on their communication range and placement. Moreover, considering their scenarios in connection with the environment.

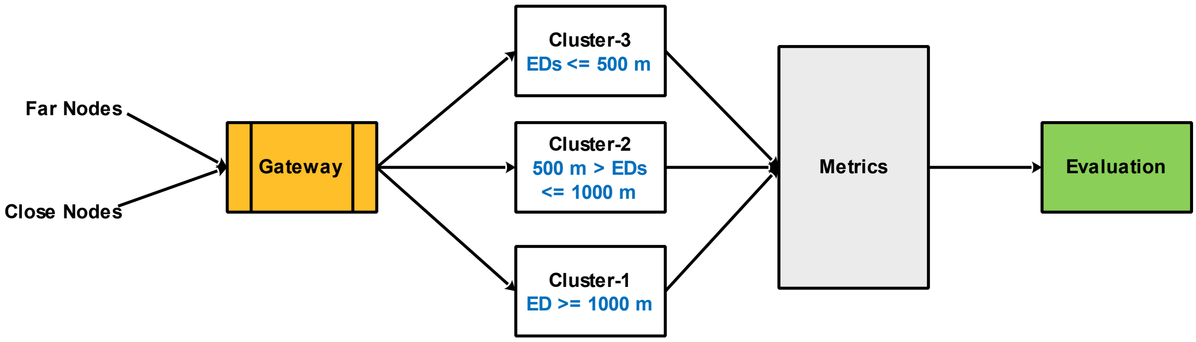

Figure 5.30: Analysis framework for distance scenario

A. Cluster-3:

Impact of placement distance

In Cluster-3, based on distances, we evaluated the performance of nodes at a distance of less than 500-metre (node $\leq$ 500 m) from the gateway. Figure 5.31 shows the distances where the longest range was 0.41 km, and the shortest 0.18 km. The lowest RSSI value reached for this cluster was -108.29 dBm and the highest was -95.02 dBm as shown in Figure 5.32. Although RSSI is affected by distance in most cases, the node at building-39 yielded the lowest value at a range of 0.20 km compared to the longest range in this cluster that was 0.41 km located at building-34, which yielded -102.86. From Figure 4.3, it is clear that the two nodes do not have the same or similar link profiles. The link profile for the node at building-39 consists of a building, a hill, and some vegetation, whereas the link profile for the node at building-34 consists only of vegetation and uphill transmission due to the location of the gateway.

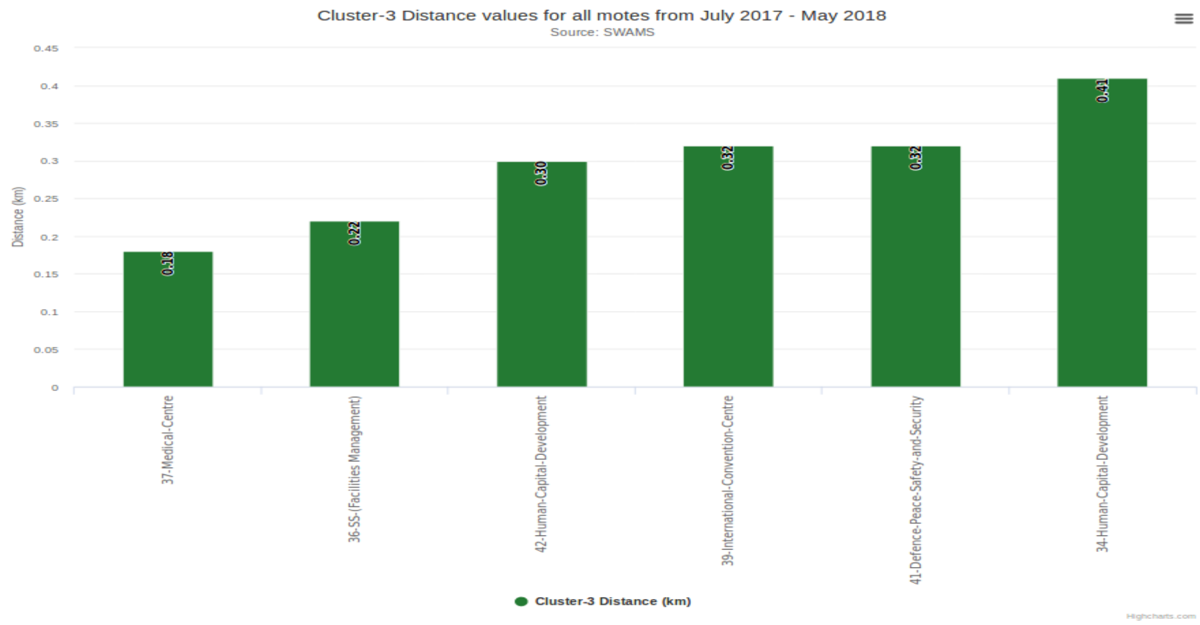

Figure 5.31: Cluster-3 distances

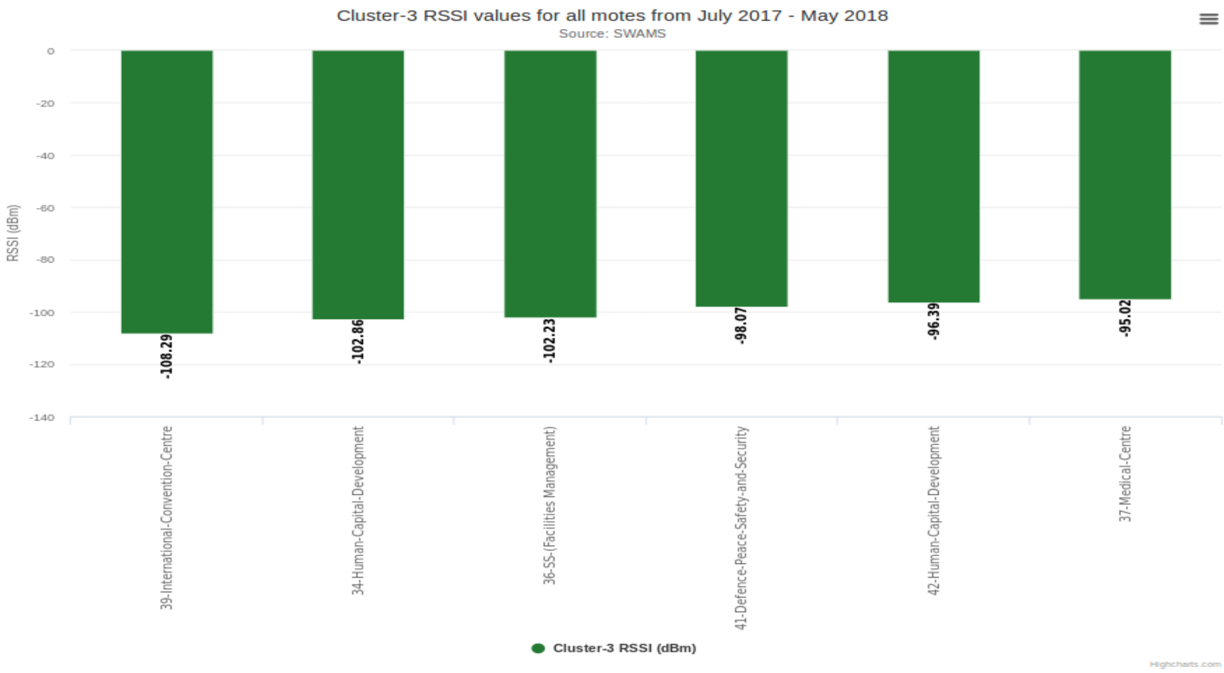

Figure 5.32: Cluster-3 average RSSI values

Impact of physical obstacles

In addition to the effect of distance on the RSSI, physical obstacles also have a huge impact on the RSSI. The node at building-36 is also located behind a building on a water pipe running through the building's wall as shown in Figure 5.33; however, due to a slight difference of distance compared to the node at building-37, it yields a lower RSSI value of -102.23 dBm.

The nodes at building-42 and building-41 are close to each other as can be seen in Figure 4.3, and indeed their RSSI results are close to each other, with building-42 having an average RSSI value of -96.39 dBm and building-41 with -98.07 dBm. In addition, while these results are reasonable, we have to consider other metrics to see the correlations. Lastly, at this point RSSI remains affected by the distance as can be seen in that the closest node to the gateway yielded the highest value.

Figure 5.33: Node at Building-36

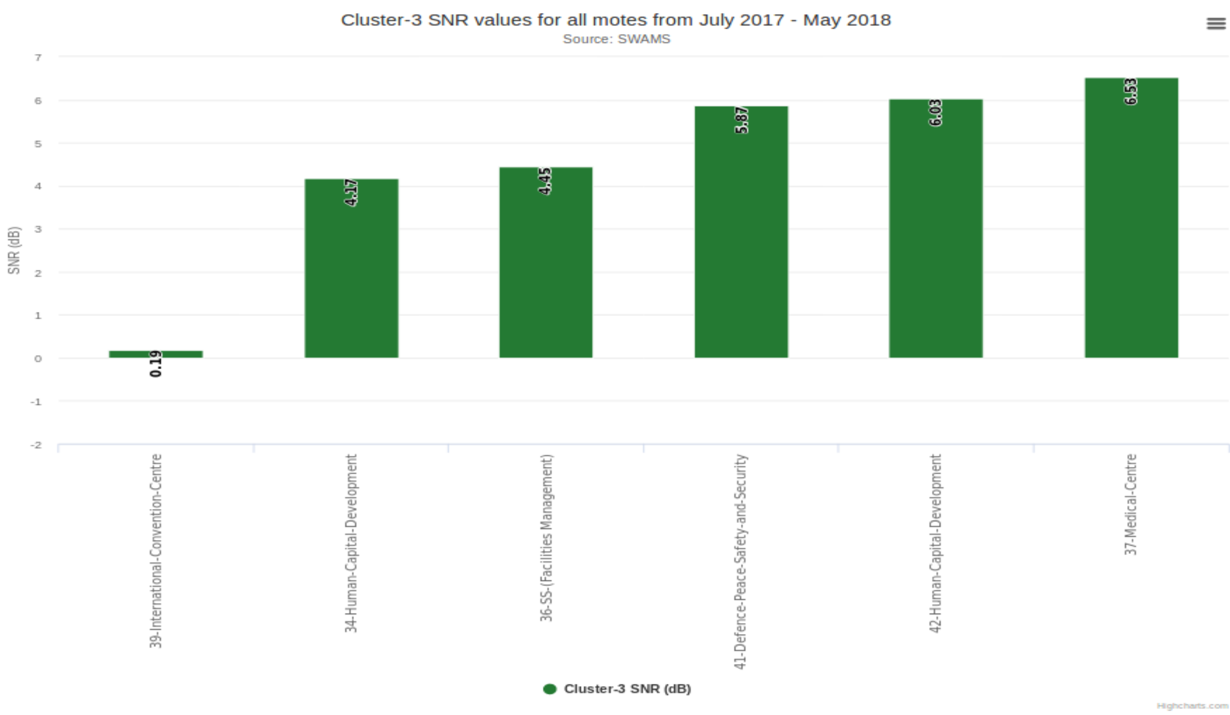

Figure 5.34: Cluster-3 average SNR values

So far, the relationship between the LoRa RSSI and SNR is becoming evident, using the results in Figure 5.34, we can see how the node at building-39 is the only one with a low SNR value corresponding to a very low RSSI value in Figure 5.32 and vice versa with building-37. We can also see how closely the SNR results for building-34 and building-36 are, and they correspond to the results in Figure 5.32. Moreover, building-41 and building-42 also have close average SNR values. Closely examining the node at building-39, it yielded a very low average SNR value and it does not really match the average RSSI value in Figure 5.32. This prompts a closer look at the overall performance throughout the nodes' lifetime. Using graphs in Figure 5.35 and Figure 5.36 we can see that the node started operating at a negative SNR value for almost two months since our data collection tool was deployed, it then increased and fluctuated around the zero value throughout, which then became the average SNR as shown in Figure 5.34. The patterns in both Figure 5.35 and Figure 5.36 are similar a fact which verifies that indeed the RSSI corresponds to SNR in LoRa networks. Lastly, we can conclude that the presence of the hill structure in the link path for building-39 introduced significant noise to the link, and attenuated the SNR greatly.

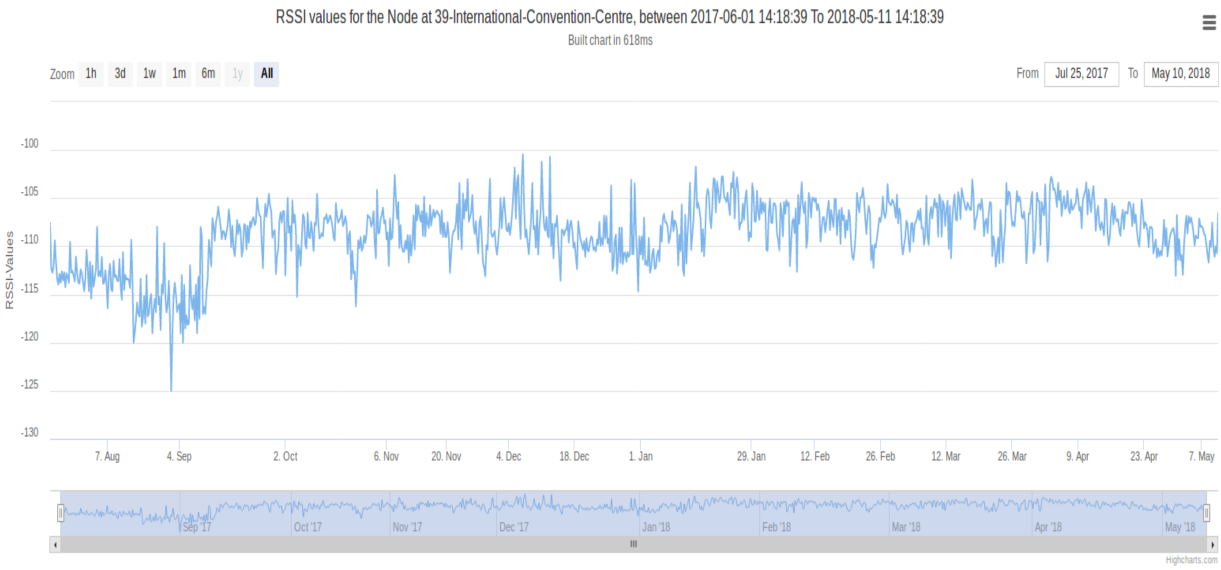

Figure 5.35: RSSI for Building-39

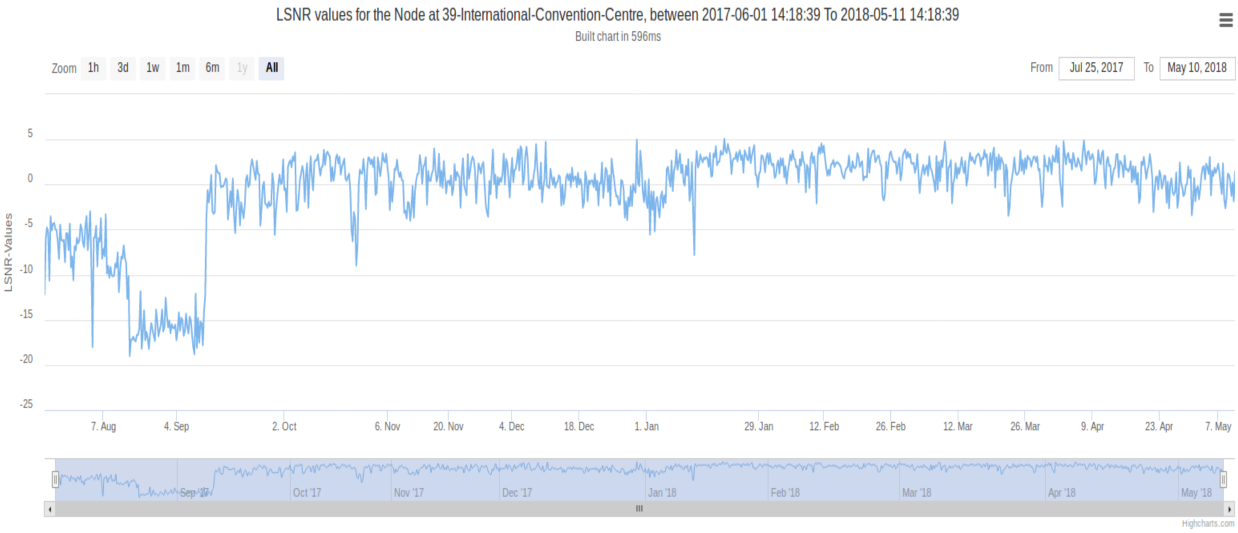

Figure 5.36: SNR for Building-39

The SF for cluster-3 is common for nodes with similar link profiles. The node at building-34 fluctuated through different SF values using ADR as shown in Figure 5.38. Because no objects interfered with the link except for vegetation, as compared to other nodes in this cluster this resulted in the node mostly using effective SF values and ended up yielding an average of SF 9. Figure 5.39 to Figure 5.42 show SF for nodes located beyond obstacles, these nodes as per the graphs have a similar SF pattern. For almost six months, the nodes maintained the use of SF 12, and ADR took effect mid-December for all nodes and they started alternating between usages of different data rates. This effect was caused by an update of the LoRa network server that was carried out during that time. Moreover, Figure 5.37 shows that both nodes at building-37 and building-42 yielded average SF values of 12 throughout and ended up disconnecting from the network.

The reason why the nodes disconnect from the network after some time depends on their deployment location (placement). The sensor node experiment carried out showed that the device had a cut off voltage of 3.2V, which is close to the full battery value of 3.7V to 4.2V maximum. We found out that when the node is located in a shadier place and at the same time situated close behind an obstacle, it is bound to go off due to the sun not reaching the node solar panel to charge it. Nodes behind buildings use settings that are energy hungry, for instance using the SF 12 that results in the node spending extended time on air (TOA). In addition, nodes behind buildings use FEC-CR, causing multiple retransmissions by the node.

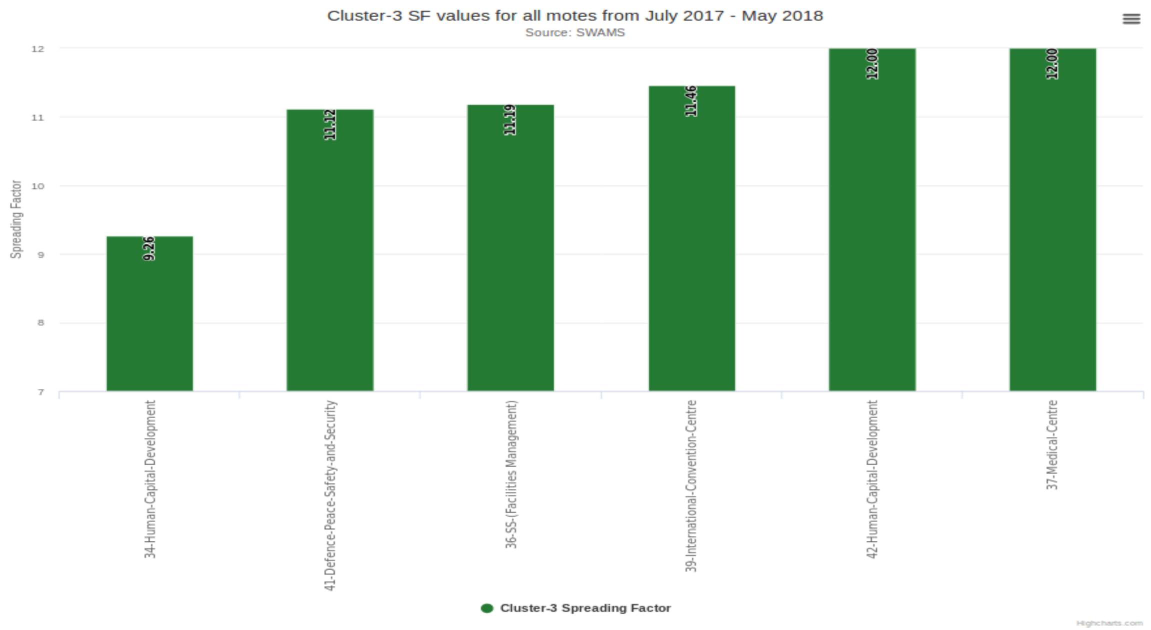

Figure 5.37: Cluster-3 average SF values

Usage of FEC-CR increases the reliability of the network and good PDR is achieved. However, it comes at a cost of using energy draining settings. Sequence numbers as mentioned, present the performance of the node concerning parameter adjustments to enable reliable transmissions. Using the sequence column in Table 5.3, we can see that the nodes for cluster-3 performed fairly well, with the node located in an open space reaching a higher sequence value of 733. Moreover, the worst performing node in this cluster having three as the highest sequence value it could reach. Lastly, although we identified the best performing and worst performing nodes for this cluster, because of FEC-CR all nodes achieve over 97% PDR as appears in Table 5.3.

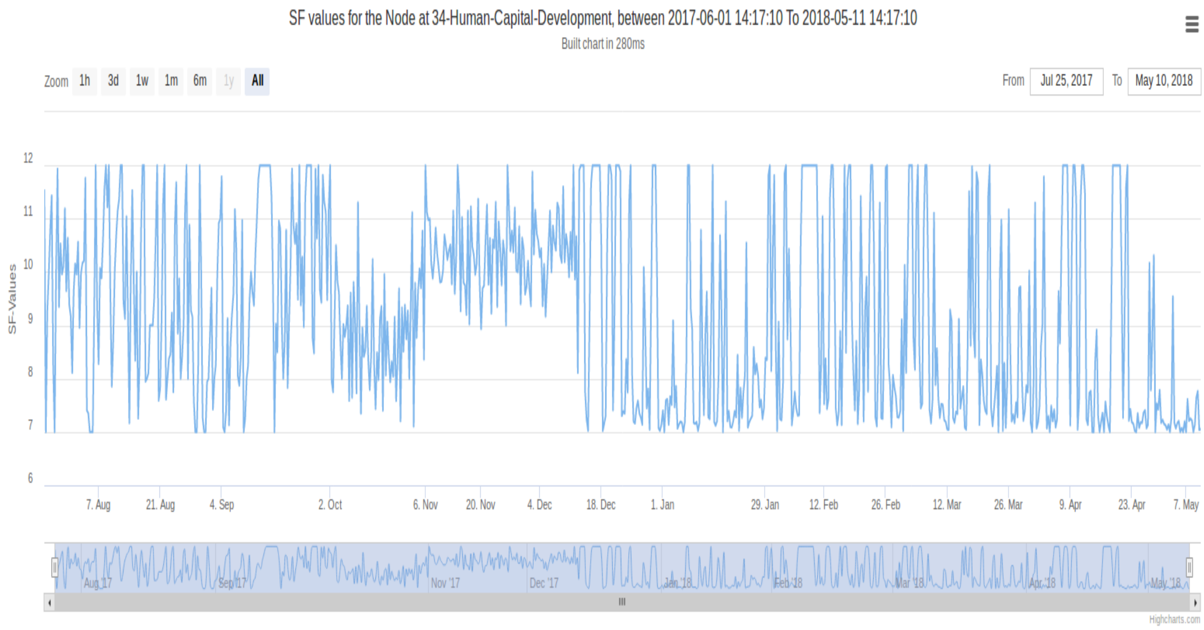

Figure 5.38: SF for Building-34

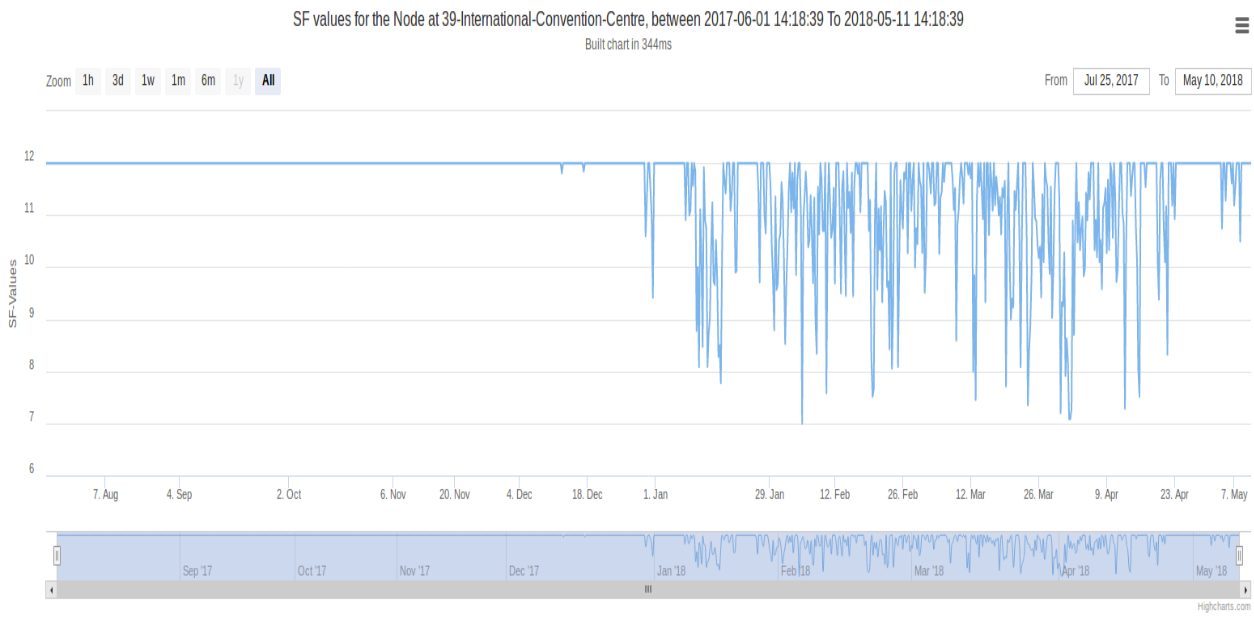

Figure 5.39: SF for Building-39

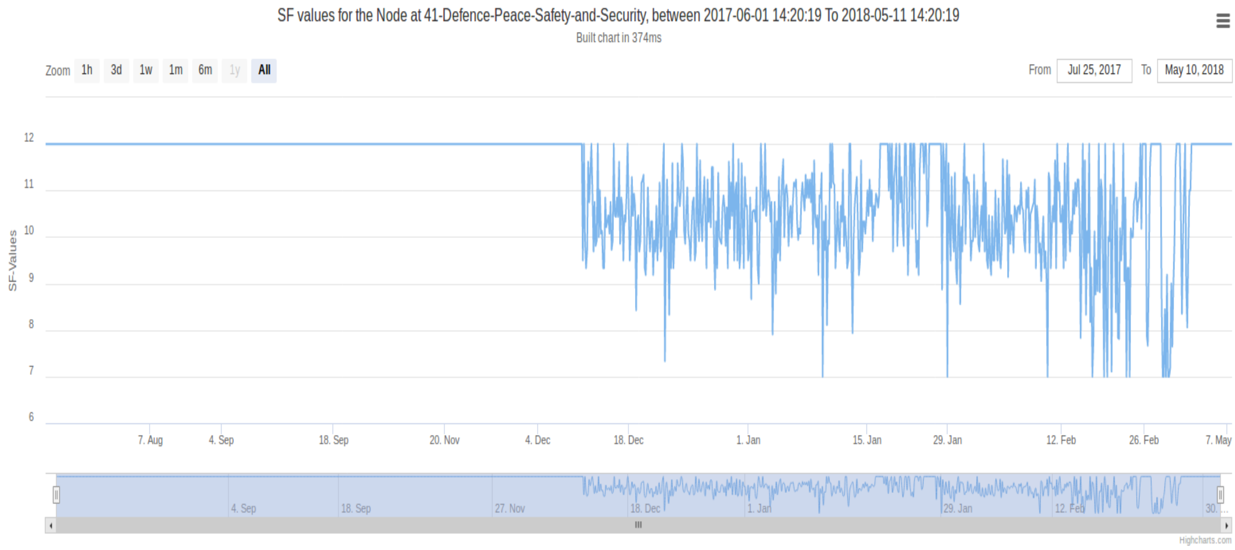

Figure 5.40: SF for Building-41

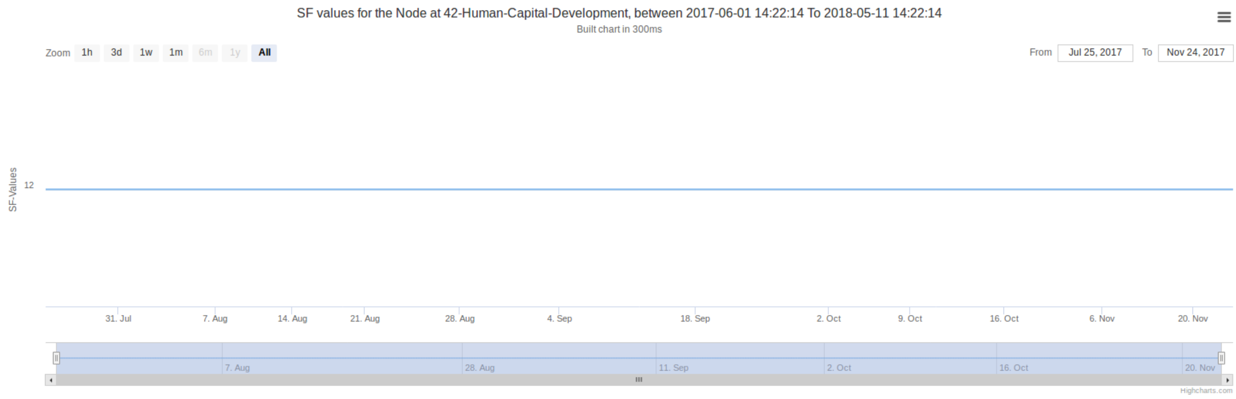

Figure 5.41: SF for Building-42

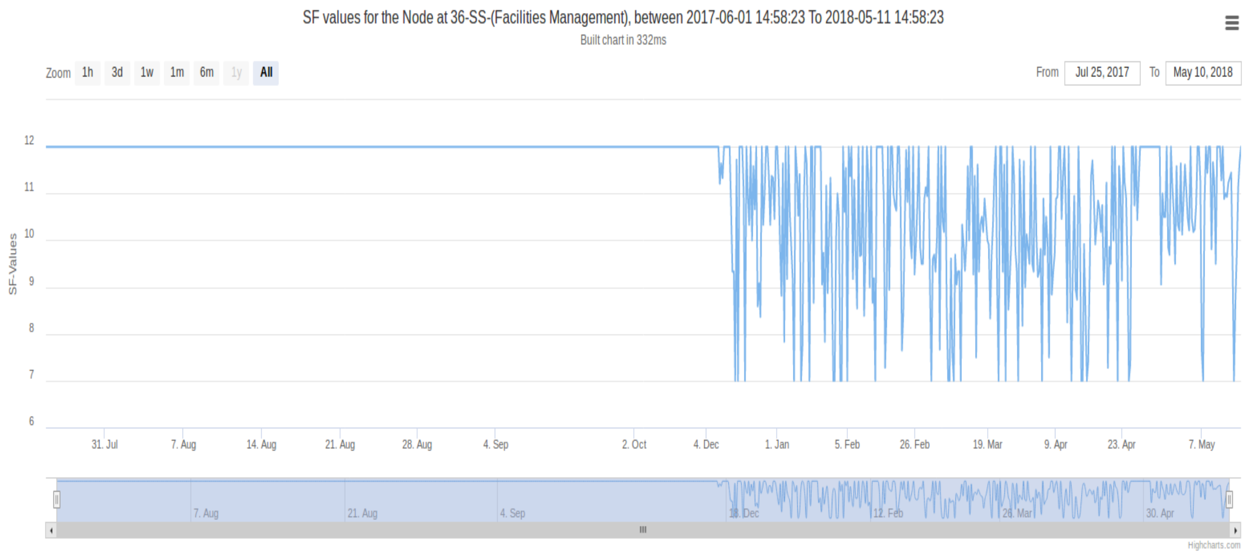

Figure 5.42: SF for Building-36

B. Cluster-2:

Impact of Placement distance

Cluster-2 consists of nodes with a distance greater than 500 meters and less than 1 kilometer (500m > EDs ≤ 1000m) as shown in Figure 5.43. Compared to other clusters, this cluster has more nodes. The findings in this chapter will support, extend, and verify thus far findings from cluster-3.

This cluster does not have a single consistent best performing node across all the evaluation metrics, which is an interesting finding. However, the three best performing nodes for this cluster are identifiable on the graphs. For RSSI, the node at building-20 gave the best results, for SNR it was building-19, building-3A for SF, and lastly as per Figure 5.49 building-3A again for sequence values. All these nodes are located in an open space, meaning they do not have buildings blocking their links except vegetation, which is available for almost all nodes.

Starting with the RSSI node at building-20 was -86.79 dBm, we can compare it with that at building-19 at -87.71 dBm, these results were close because the nodes, also, are located close to each other. The reason why building-20's node got the highest values against building-19 is in the distance (range). Nodes having longer range result in lower RSSI and worse when there are obstacles and interference in between as seen in cluster-1 and the first analysis. However, the node at building-3A is much closer to the gateway as compared to the two buildings and it gave lower RSSI although used the lowest SF values as shown in Figure 5.45. The argument for this result is that the use of higher data rate, that is utilizing SF 7 makes the link fragile to interference and external noise as compared slow data rate of SF 12 where the sensitivity of the link is increased.

As shown in Figure 5.46 and Figure 5.47 the node started off with alternating SF values. However, after the update of the mLinux OS, SF 7 was consistently used, and the RSSI can be seen decreasing and maintaining the same trend corresponding to the SF graph. Therefore, higher data rates will yield lower RSSI values. Another remark can be made that the LoRa NS sets closer nodes to use higher data rates provided their link budget is not costly. Hence, in Figure 5.45 the SF values are in order according to node distances and the link profiles.

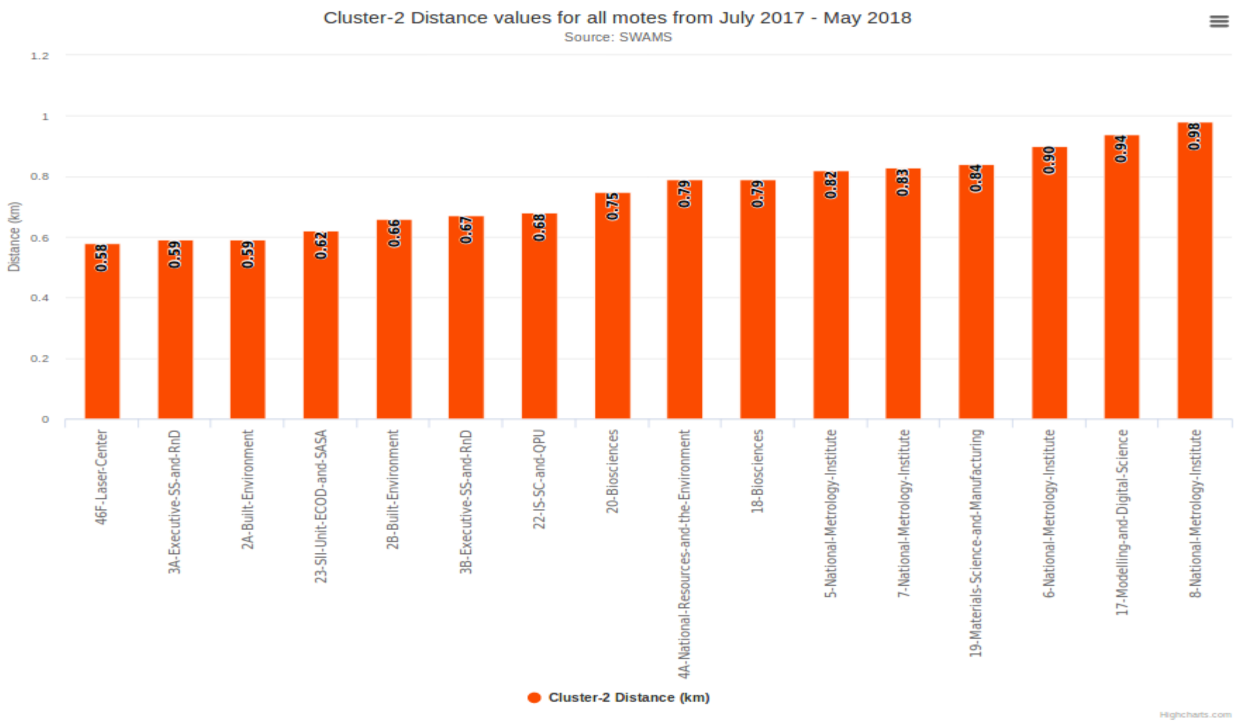

Figure 5.43: Cluster-2 distances

Impact of Physical objects

In this cluster the worst performing nodes with regard to RSSI are building-5, Building-6, and Building-8 compared to other nodes within cluster-2. These nodes are located around the same locality- they are behind three close tall buildings blocking the signals. The node at building-7 is also located at the same locality but its transmission did not pass through the same tall buildings, and it still yielded better results compared to these three nodes. This means the tall buildings influenced the results more than shorter buildings found in front of other nodes. As shown in Figure 5.48 the average SNR value for the node at building-5 was -2.53 dB, the lowest values thus far. The results are due to where the node was situated, it was situated on a water pipe running through a wall and in front of the node was a tall building, as compared to the nodes at buildings-6 and 8. Moreover, the node has an average SF value of 12 as shown in Figure 5.45; the use of highest SF throughout verifies that the link was costly.

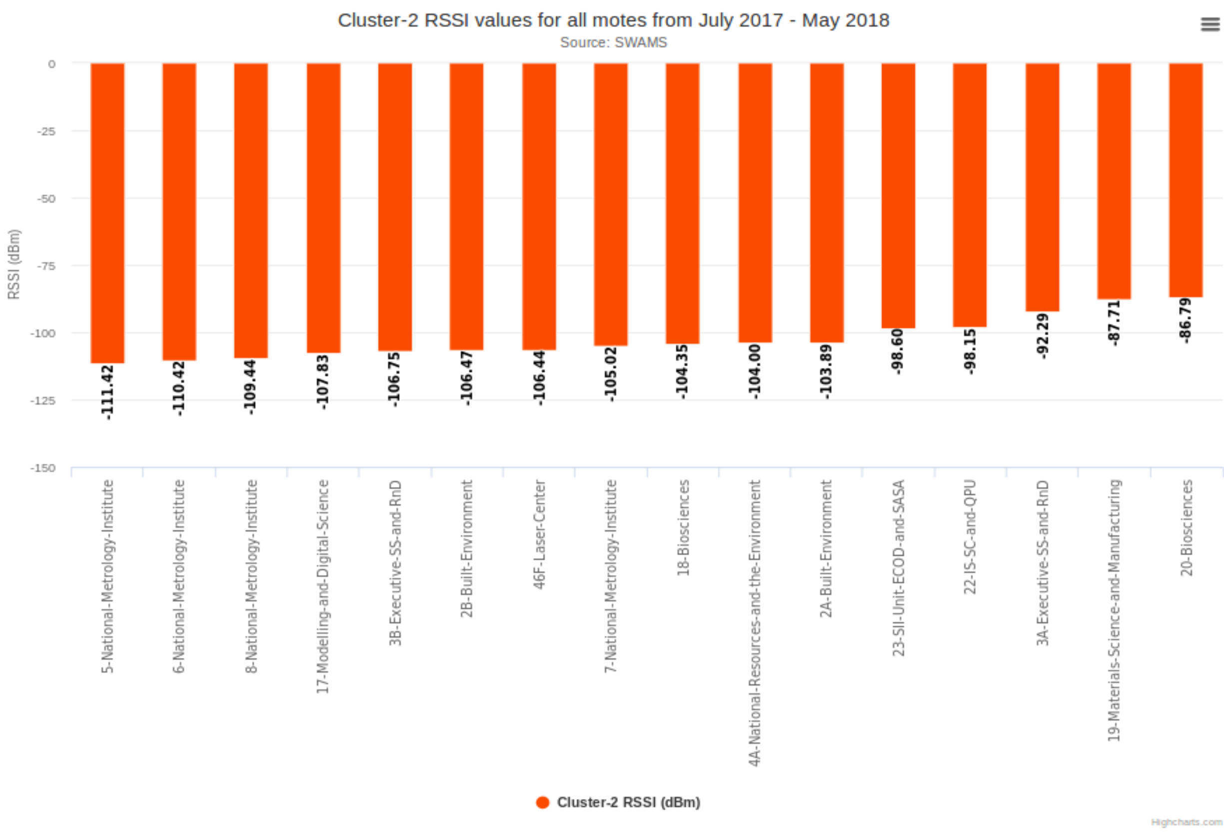

Figure 5.44: Cluster-2 average RSSI values

The node at building-6 was able to use fluctuating SF values because there was some space in front of the node before the tall buildings blocked the LOS. This resulted in an average of 10.80 as shown in Figure 5.45. The node at building-8 was deployed on a water pipe running through the building wall. Hence, it averaged to SF of 11.88 with SF 12 being the mode value. In addition, it turns out the node also went off and disconnected from the network by the end of December 2017, this behaviour was the same as the node behaviour at building-37 in cluster-3. However, using the sequence graph on Figure 5.50 we can see that the node started stabilizing while reaching higher sequence values after the gateway mLinux OS was updated mid-December. Lastly, the device was not getting enough sunlight to charge the battery using the onboard solar panel and hence it went off.

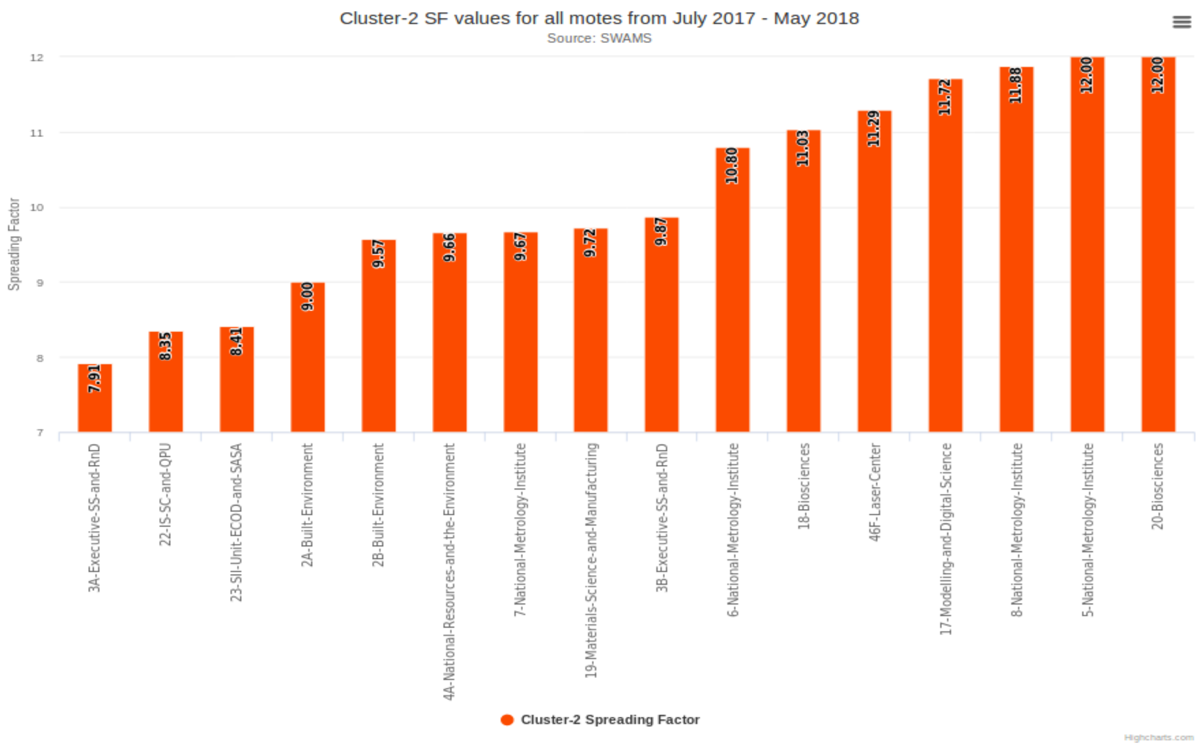

Figure 5.45: Cluster-2 average SF values

The node at building-19 gave the highest SNR of 7.95 dB, followed by building-3A with 7.23 dB then building-20 with 6.97 dB as shown in Figure 5.48. SNR values are mainly affected by the presence of additional noise on the signal in transmission. The nodes at hand did not have obstacles in their link profiles. Hence, they yielded good results, the node at building-3A come in second place on the SNR measure. This meant the higher data rates affects the sensitivity of the signal rather than introducing external noise. The cluster-2 findings are linked to the preceding analysis and added more findings and insights.

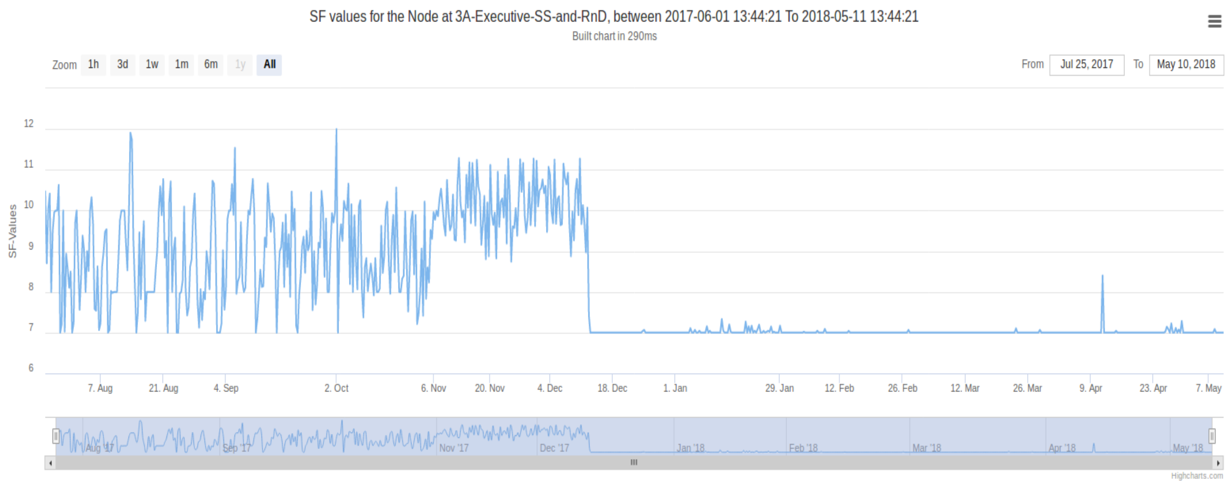

Figure 5.46: SF for Building-3A

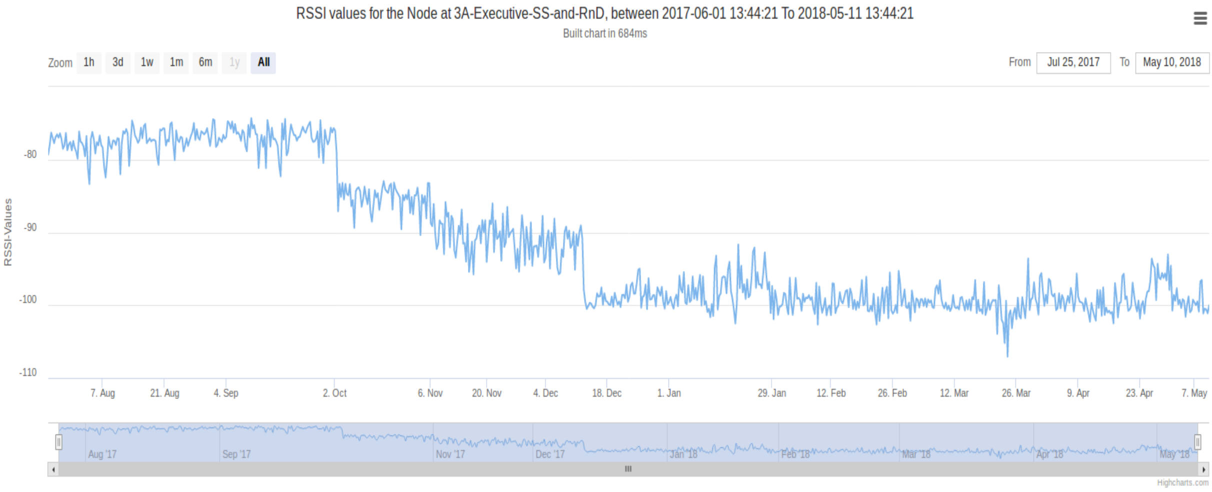

Figure 5.47: RSSI for Building-3A

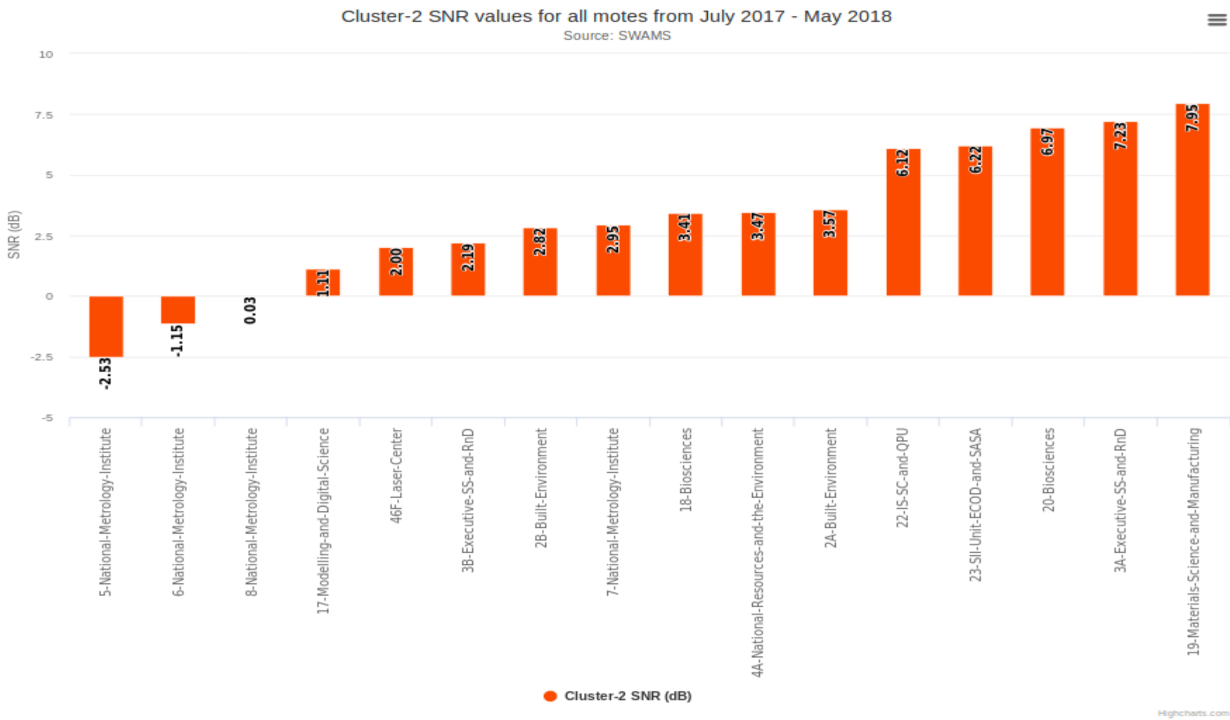

Figure 5.48: Cluster-2 average SNR values

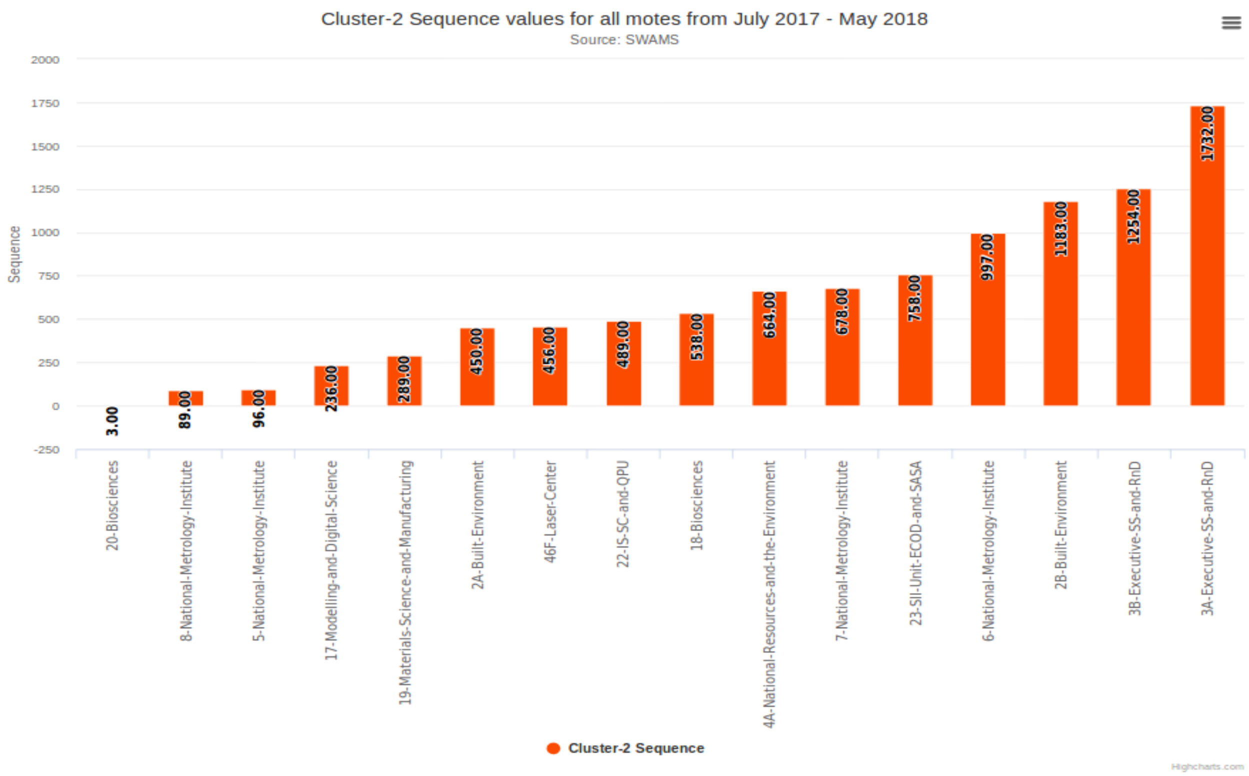

Figure 5.49: Cluster-2 Sequence values

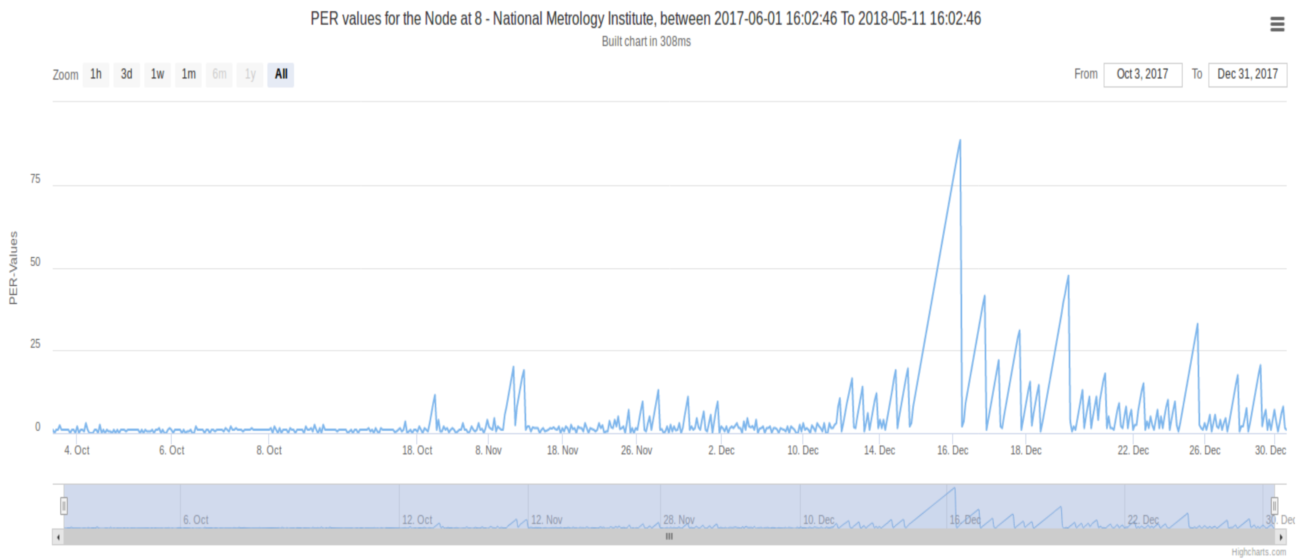

Figure 5.50: Sequence graph for Building-8

C. Cluster-1:

Impact of placement distance

In cluster 1, we analyzed the nodes of over 1 km (nodes ≥ 1000 m) range with respect to the gateway. The node distances are shown in Figure 5.51. The first analysis for the furthest and closest nodes analyzed, in detail, the performance of the node at building-14B, which in this cluster was one of the worst performing nodes. Figure 5.52 shows a graph of the average RSSI values for this cluster. A pattern of behaviour is observable from the graph, the worst performing nodes yielded values of about -108 dBm. The second pattern is of the mid performing nodes sharing the value of about -100 dBm. The highest value achieved for this cluster's RSSI was -89.03 dBm, which was a good value for a long-range node. We started by analyzing the worst performing nodes with respect to RSSI excluding the node at building-14B, this left us with nodes at building-16A, building-15 and building-50, these nodes yielded -108 dBm decimal. What these nodes have in common is they are located behind buildings as shown in Figure 4.3.

Impact of Physical Obstacles

From the preceding analysis, we saw that obstacles and the link range attenuate the RSSI. In addition, RSSI and SNR graph patterns correlate when dealing with obstacles. As shown in Figure 5.53, therefore, nodes yielded significantly lower average SNR values.

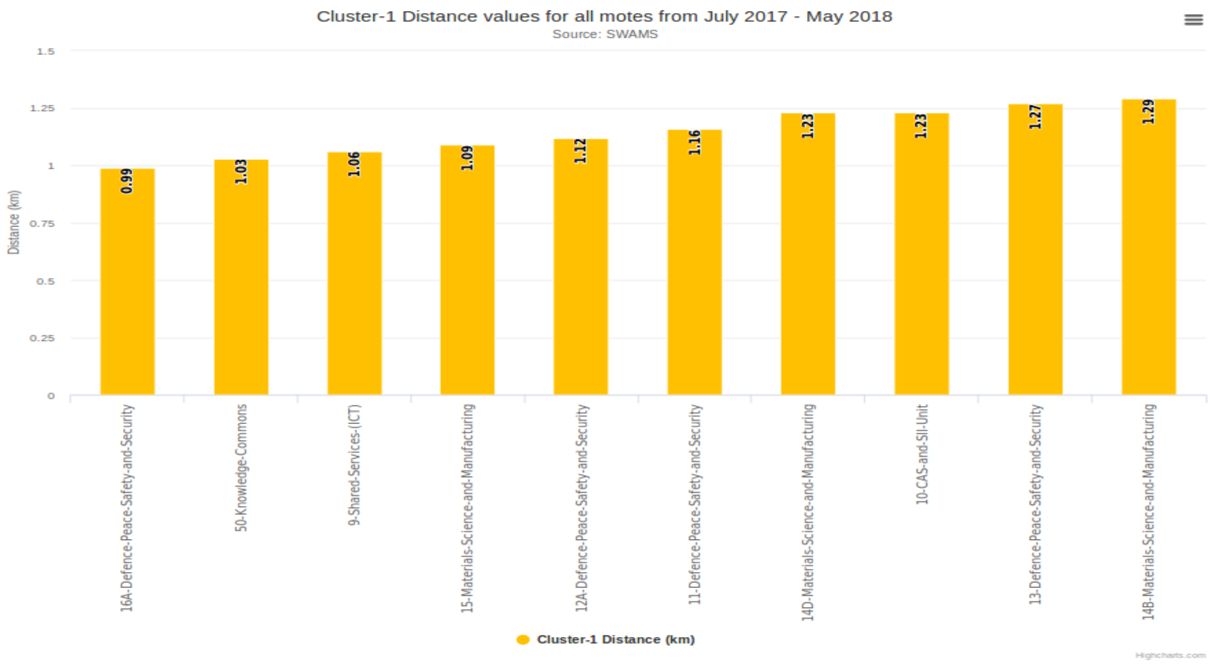

Figure 5.51: Cluster-1 distances

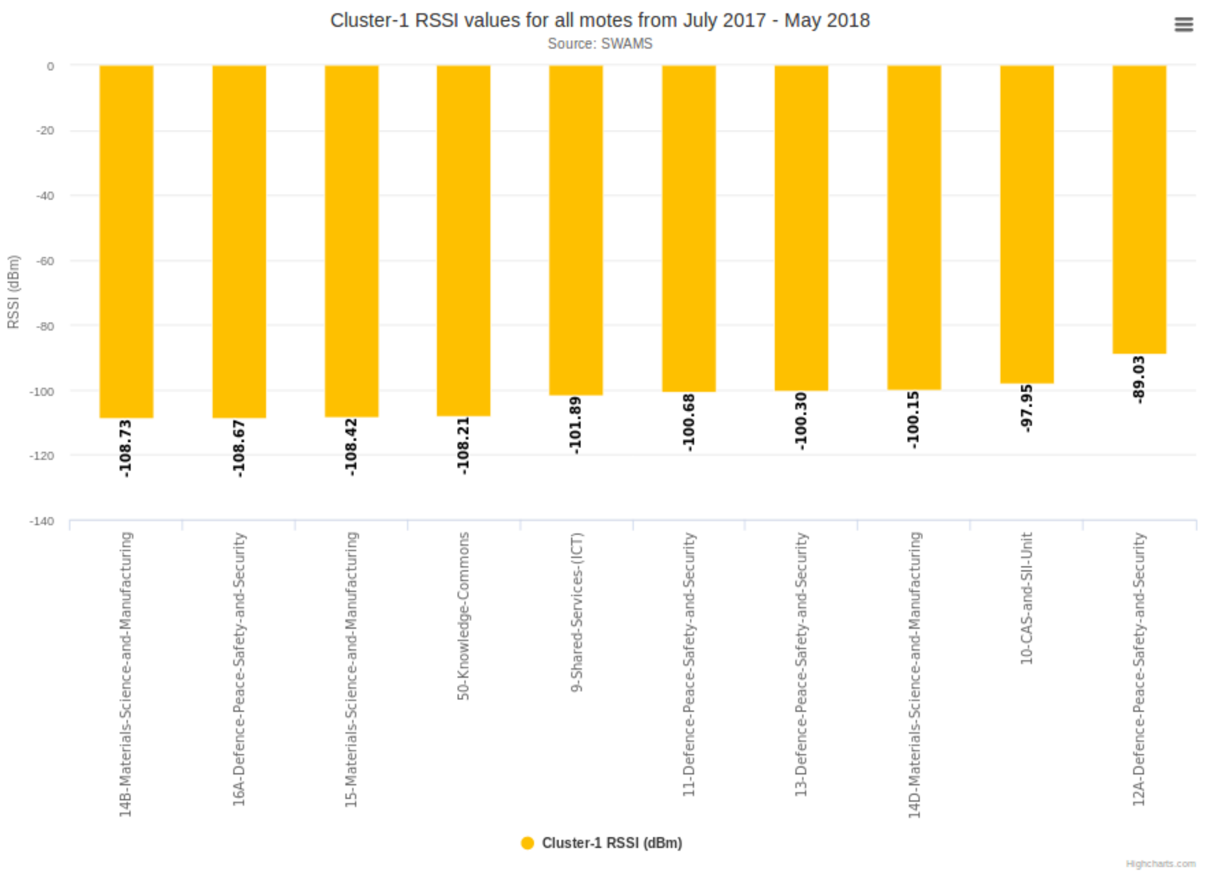

Figure 5.52: Cluster-1 average RSSI values

The best performing node for both RSSI and SNR was the node at building-12A. Its results verify how obstacles affect both metrics because the node as seen in Figure 4.3 was located in an open space with respect to the direction of the gateway and it had a greater range than the aforementioned worst performing nodes for this cluster but still performed better than them. As like some nodes from the preceding clusters, this node started using a constant SF of 12 up until the mLinux OS was updated, then it started alternating between different data rates (SF values) as shown in Figure 5.55. Its changed behaviour after the update was similar to that seen in Figure 5.39, Figure 5.40, and Figure 5.42. With this amount of evidence, we can confirm that the previous LoRa NS version was not effective enough in optimizing the network links.

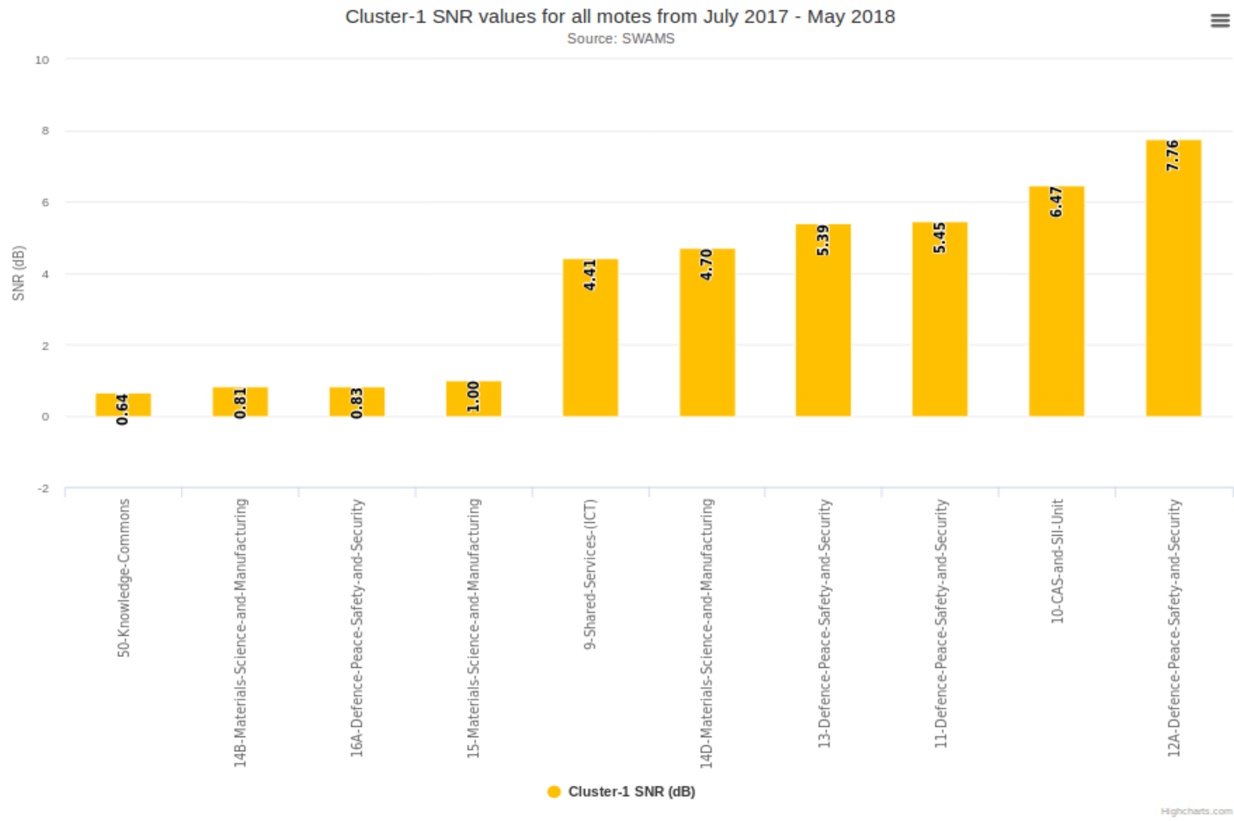

Figure 5.53: Cluster-1 average SNR values

SF, on the other hand, does not correspond directly to the RSSI and SNR results as shown in Figure 5.54. However, the worst performing used the slowest data rates as seen they fall on the average SF 10 going up. In addition, higher SF's are used when the link strength is weak so to introduce sensitivity. However, using higher SF is costly to nodes. Using Figure 5.54, we can see there is a significant difference provided by the three nodes at building-10, building-13, and building-11. They all yielded averages of SF 8 although they had similar link profile as the node at building-12A. The argument for their results is that they started-off using ADR unlike the node as building-12A, which started using ADR after the mLinux update. Figure 5.56 shows how their results relate, after the update the nodes used lower SF (high data rates), with SF 7 being used the most. These results were expected because when there is less interference on the link the LoRA NS will select the efficient setting for nodes provided the link strength correlates. Lastly, since the node at building-12A had the same link profile as the aforementioned nodes we can argue that if it had started off using the ADR it would have yielded almost the same results.

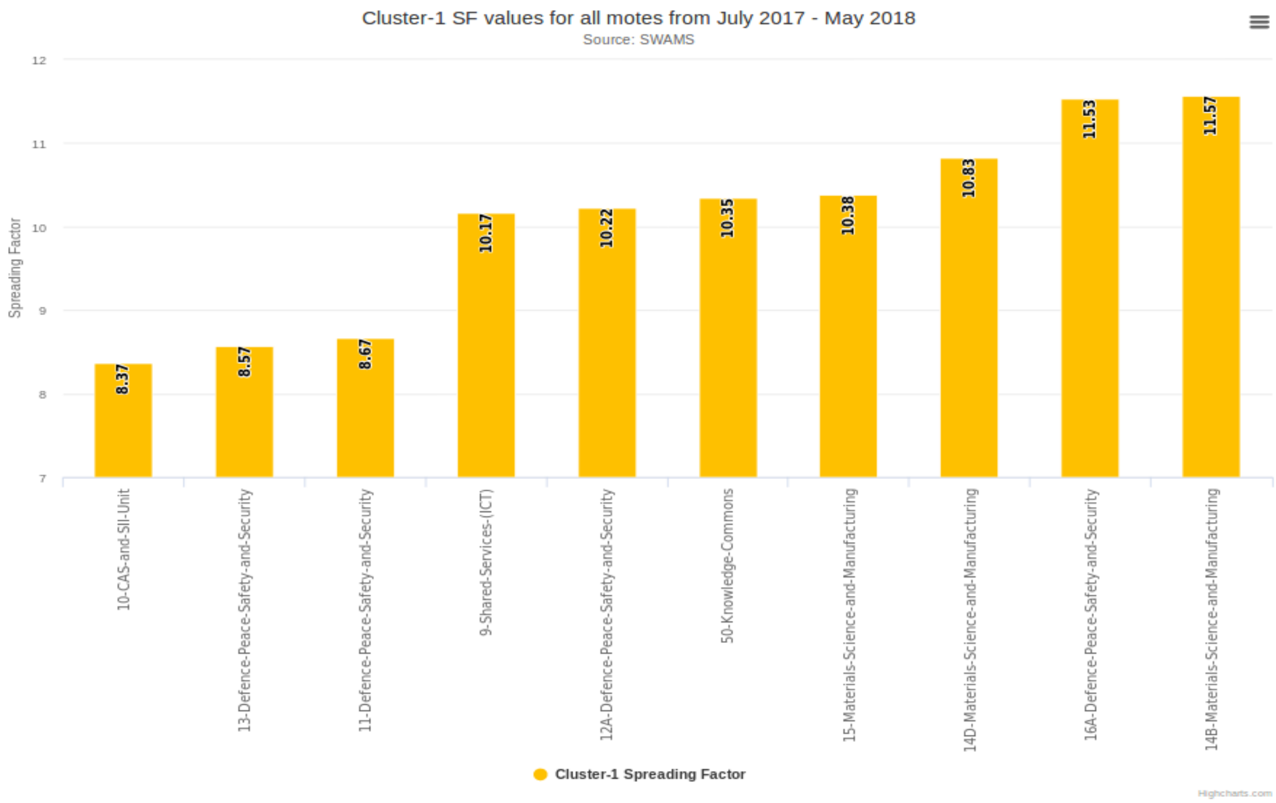

Figure 5.54: Cluster-1 average SF values

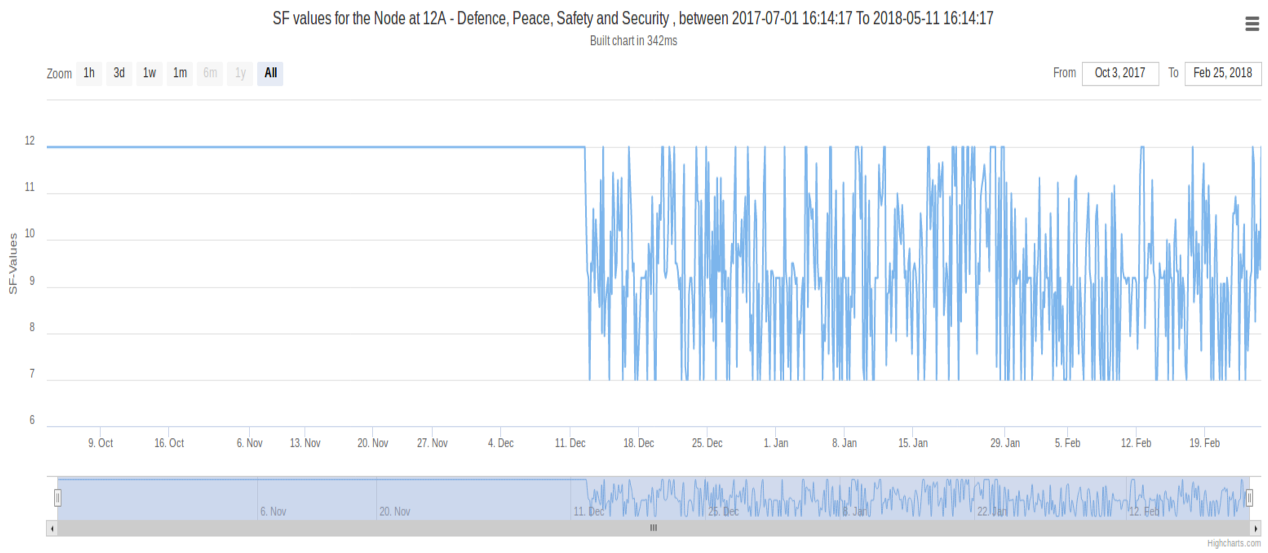

Figure 5.55: SF graph for Building-12A

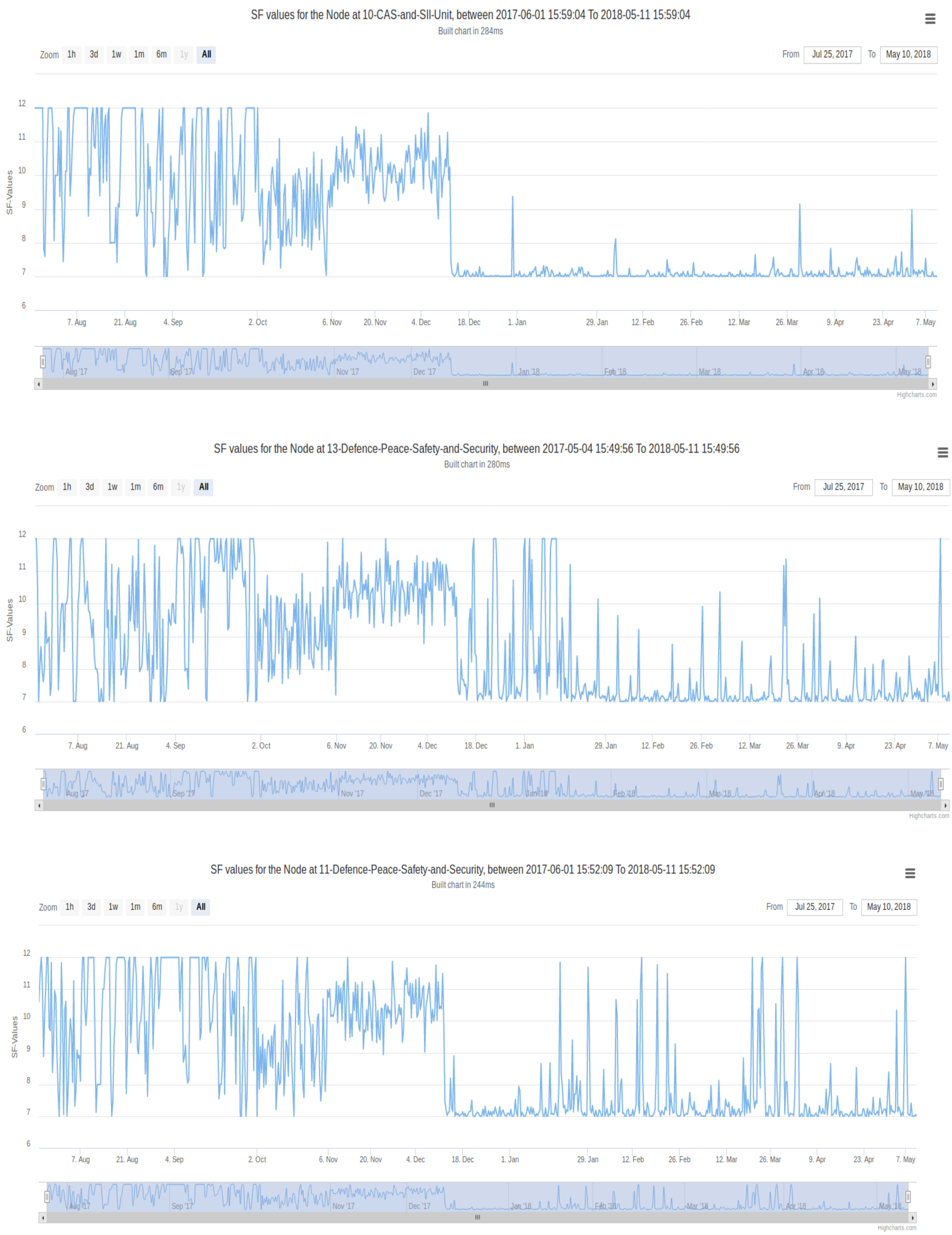

Figure 5.56: Building-10, Building-13, and Building-11 SF graphs

5.5.2.3 Line-of-sight Scenario

In this test scenario, the objective was to analyze the performance of the network nodes in terms of LOS and none line of sight (NLOS). The map in Figure 4.3 shows how harsh the area of deployment was. Moreover, as discussed earlier the gateway was placed on top of a hill inside the campus. In addition, the campus has a lot of vegetation all over and the nodes were located at the ground level in water meters exposing the link to obstacles and interference which authors in [31] investigated and concluded that it did affect the performance of the network. Therefore, as a result, we observed that the vegetation was present in most nodes; however, the location of the gateway tried to minimize the vegetation effects. Although, there is a struggle of clear LOS across the nodes, their results, as per preceding analysis, were substantially affected by obstacles and hills. Moreover, during our physical observation, one node located at building-3A had a clear LOS, and so far, it has yielded good results with respect to the distance scenario analysis above. This test scenario then will compare nodes situated behind buildings and hills and those situated in an open space with regard to the direction of the link towards the gateway. Most of the effects were discussed in the distance scenario, in this subsection we aim to verify the above analysis and give an overall overview of the results.

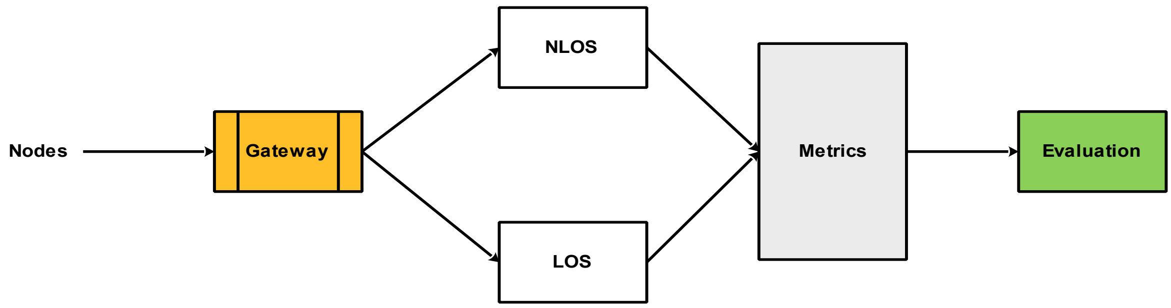

Figure 5.57: Analysis framework for Line-Of-Sight scenario

A. LOS

Impact of Placement distance

The nodes with LOS in our context yielded good performance. What can be observed from the results is how the distance attenuates the RSSI even with LOS. The nodes with short range yielded better RSSI as shown in Figure 5.58, with values greater than -100 dBm compared to long range nodes with less than -100 dBm. The lowest value as observed was -106.47 dBm. Although the highest value was -86.79 dBm, it should be outlined that the node at building-20 operated only for a short period in the presence of our data collection tool. However, we still consider its results even though we believe they would be slightly different if the node operated for an extended time but still the values would have been higher considering the relationship to other nodes in the LOS. We also discovered how the link elevation mattered. Using the map in Figure 4.3 nodes that were close but coming from the left hand side of the gateway, the side where the hill extends towards the location of the gateway, performed poorly less than -100 dBm. As compared to those coming from the right side of the gateway, where the end of the hill is a short distance from the gateway location, they performed above -100dBm.

Impact of Physical objects

The SNR for this study has been observed to be comparable with the RSSI although the findings show that obstacles, other than the distance, affect SNR badly. This scenario then becomes a good test scenario for SNR. As shown in Figure 5.59 the SNR values are all positive with the lowest being 2.00 dB. We consider the lowest value still good, considering how harsh our environment of deployment is and for the fact that LoRa can operate under a negative SNR. Overall, the graph shows good average SNR values for nodes in LOS.

From the preceding analysis, we also learned that obstacles affect the SF causing the ADR to best select the effective data rates to use for the link. As observed in Figure 5.60 the graph shows that most nodes averaged lower SF values, this verifies that the ADR allocates nodes in open space lower the SF values. This study shows that the system would have recorded lower SF averages provided the significant change observed after the mLinux OS update for the gateway, which also updated the NS. The SF started normalizing after the update; the nodes in LOS started alternating more on the lower SF values with SF 7 as the mode. Although, the nodes were not affected in the same way, those that started using SF 12 constantly yielded higher averages as shown in Figure 5.60. The node at building-20 averaged to SF 12 because it went off the network before the update. Another finding is that the NS gave those nodes close to each other lower SF values to use and adjusted accordingly with other nodes on extended ranges.

Network reliability

In this study, the sequence value was used for mainly two things, to derive the PDR, PER and to determine the performance of each node indicating whether the node was experiencing link difficulties or not. The common higher value yielded by that kind of node is 3, as can be seen in this scenario the node at building-20 performed badly as shown in Figure 5.61. In addition, the node at building-3A reached the highest sequence number as compared to all the nodes on the network. As mentioned earlier this node has a clear LOS, the profile is clear of all obstacles including vegetation. Lastly, the overall performance can be drawn from Figure 5.61 as an overall good performance for nodes with LOS.

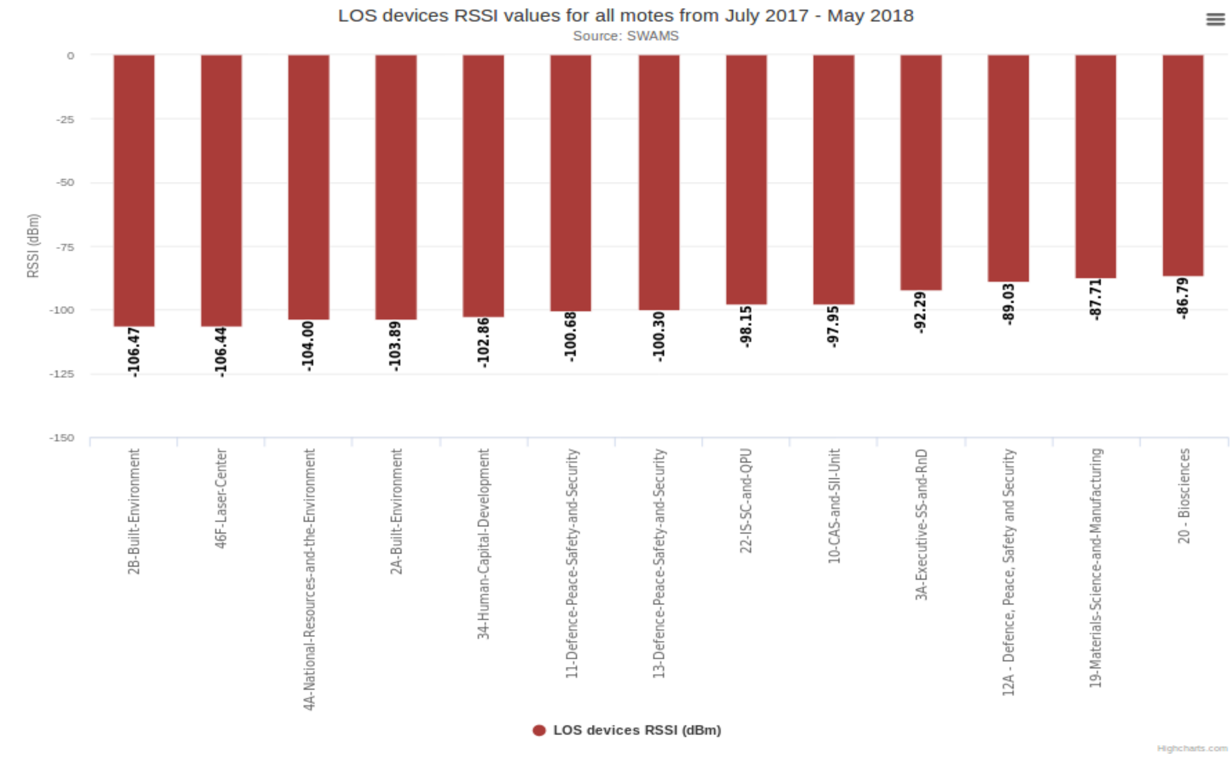

Figure 5.58: LOS average RSSI values

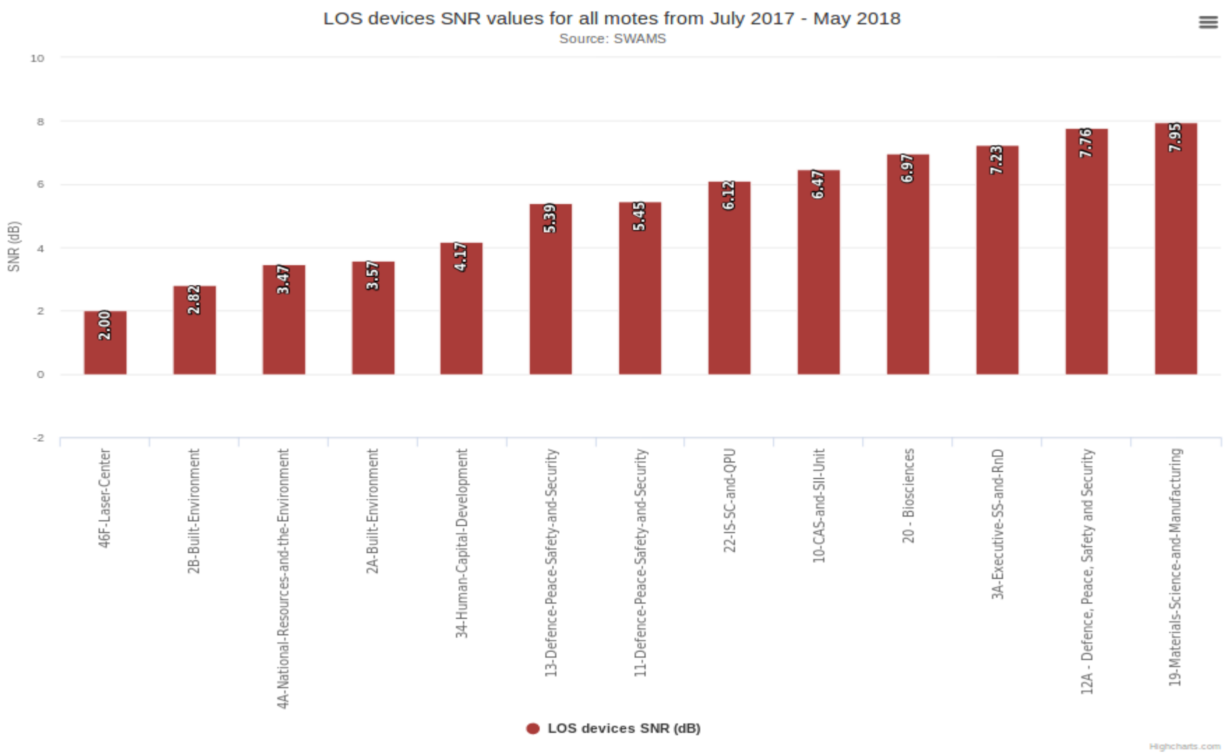

Figure 5.59: LOS average SNR values

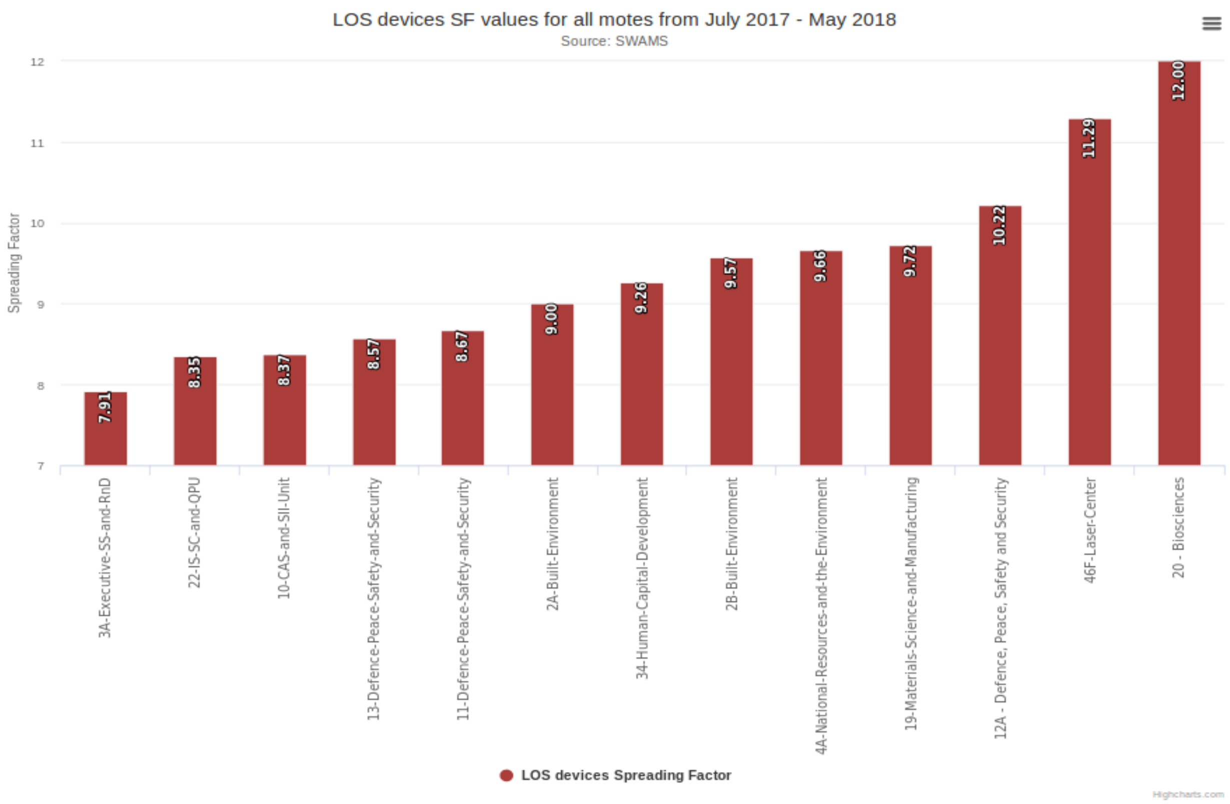

Figure 5.60: LOS average SF values

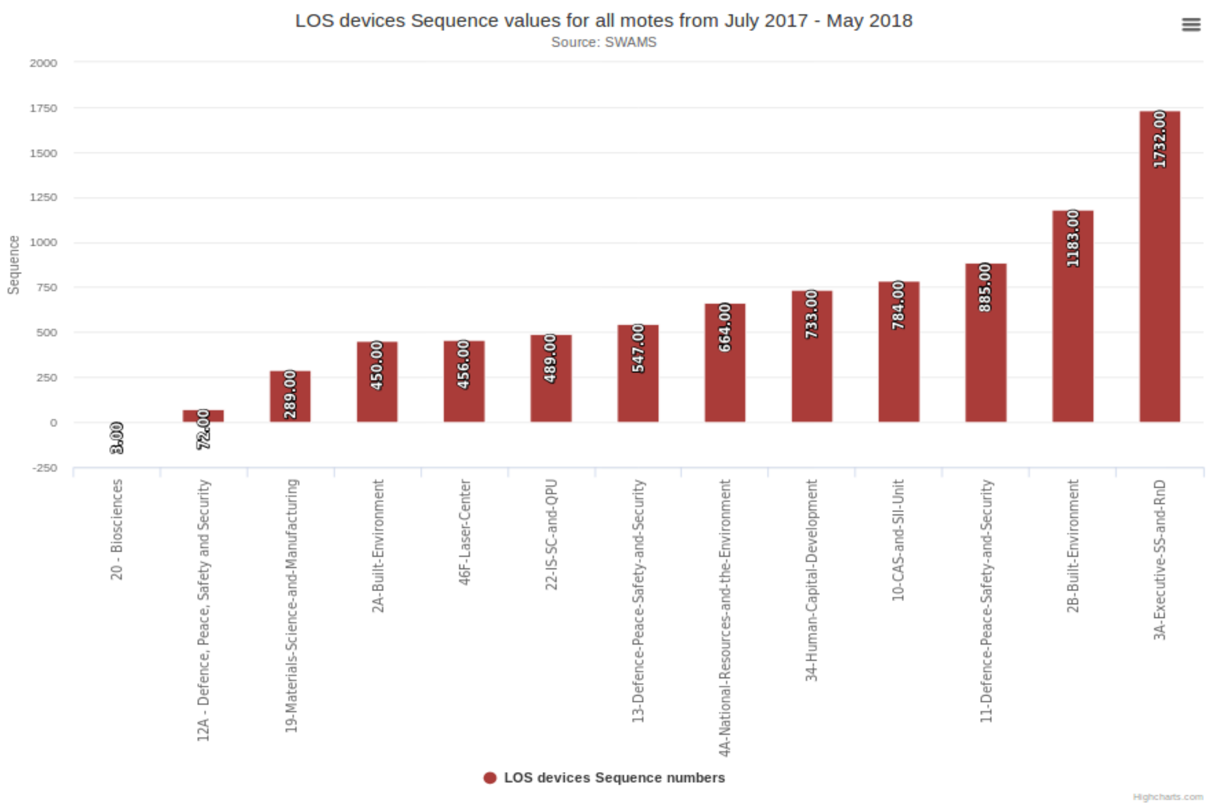

Figure 5.61: LOS Sequence values

B. NLOS

Impact of Placement distance

The overall average RSSI values for NLOS do not have a significant difference from the LOS results. However, we can observe that the values spanned lower than those of LOS did, with the lowest value being -111.42 dBm and highest being -95.02 dBm as shown in Figure 5.62. Although, the performance of LOS is a good one, thus far the findings have suggested that the RSSI does not only rely on LOS. However, LOS improves it. Also for NLOS, we can see that the RSSI greater than -100 dBm comes from the closer nodes.

Although SNR correlates with RSSI, we can observe a significant difference in results as compared to the LOS nodes. The results of this scenario give an overview of how SNR is attenuated by obstacles. Figure 5.63 shows that obstacles can attenuate the SNR up to a negative level. Only a few nodes gave tolerable average SNR, and those nodes are the ones with shorter range as compared to the long-range nodes.

Impact of Physical objects

Obstacles caused the ADR to choose higher SF values for links. It is evident in Figure 5.64; the graph is dominated by SF values of 10 and higher, with decimal SF11 being dominant. Therefore, these results verify our preceding analysis findings; that obstacles attenuate the SNR and affect it differently. Moreover, with regard to sequence values Figure 5.65 show that although the nodes do not have LOS, they are still able to maintain the communication for a long time without having to reset.

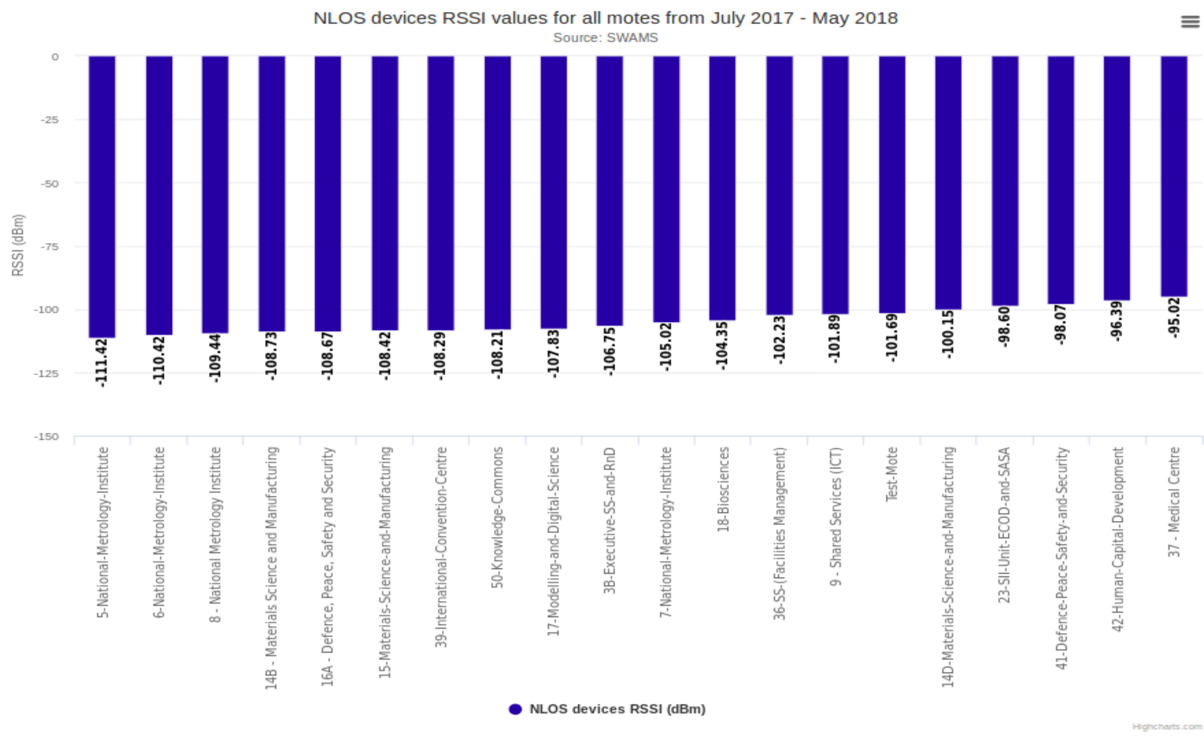

Figure 5.62: NLOS average RSSI values

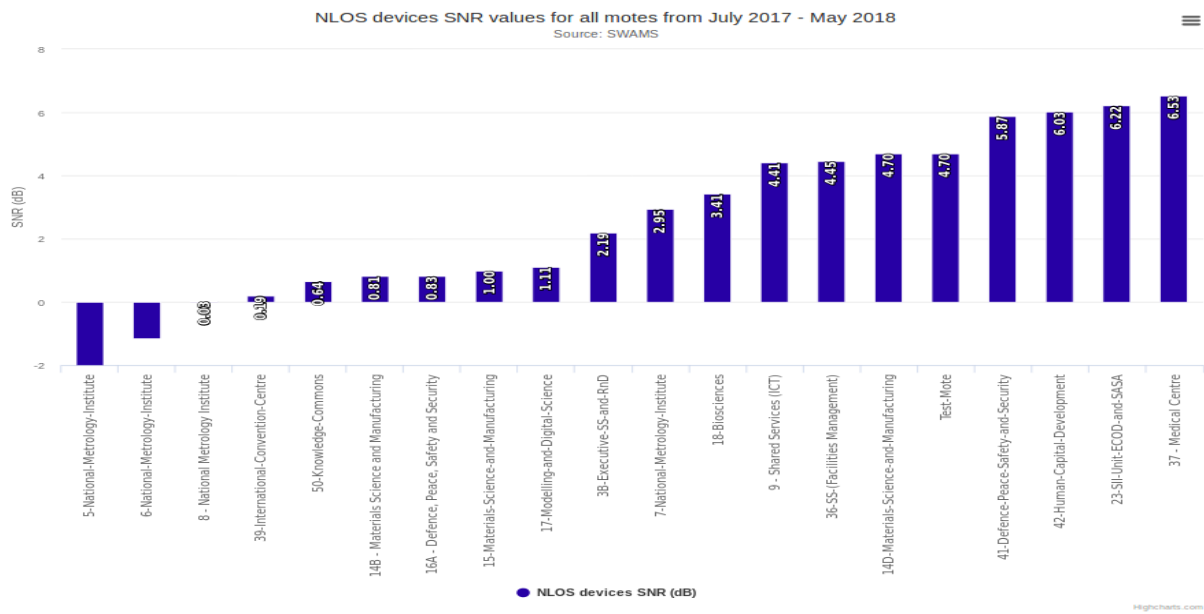

Figure 5.63: NLOS average SNR values

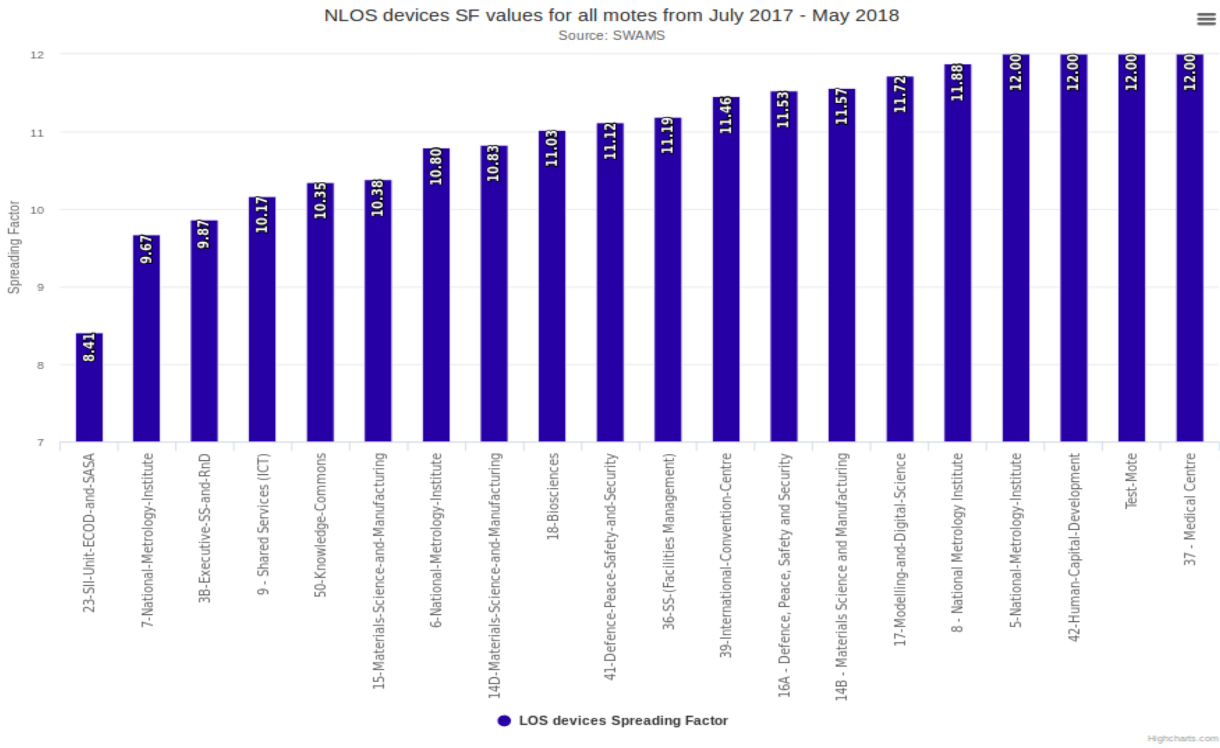

Figure 5.64: NLOS average SF values

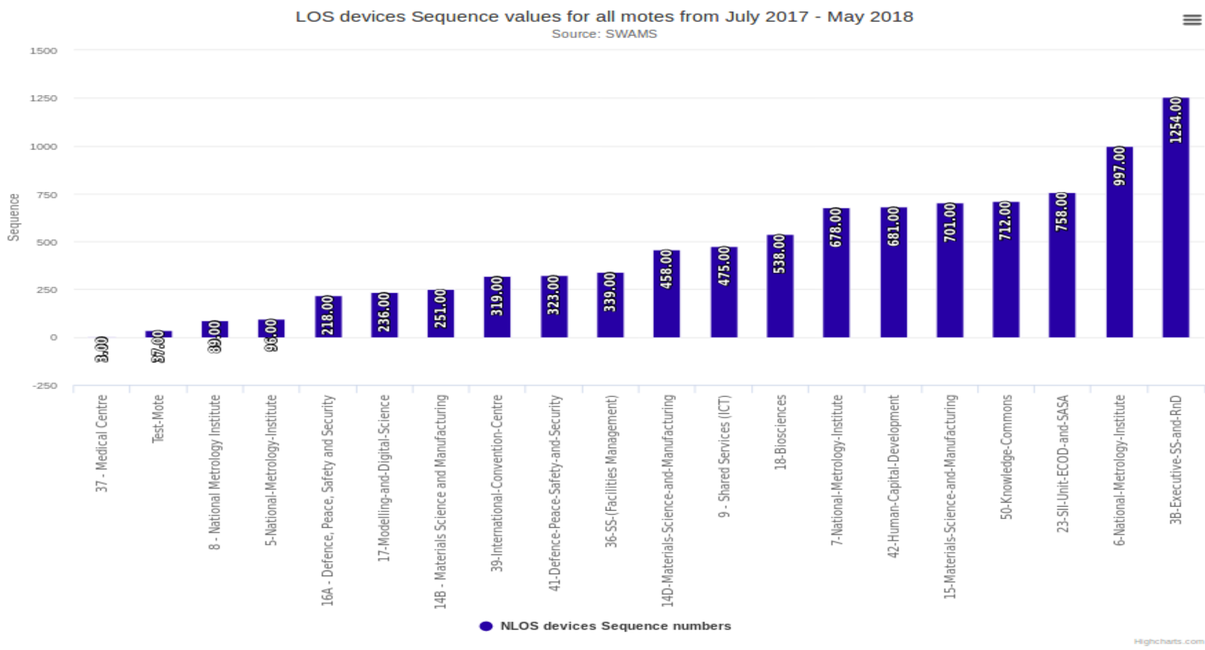

Figure 5.65: NLOS Sequence values

5.5.2.4 Physical Obstacles Scenario

This test scenario aims to analyze the performance effects caused by different obstacles present around the campus, and present in between the communication links of the nodes. In the preceding analysis, we have already identified the obstacles that influenced the performance. We observed five cases, which were, LOS, Open-Space, Single-Building, Multiple-Buildings, and Hills.

Nodes with clear LOS give the best performance regarding RSSI and SNR and are able to use high data rates provided by lower SF values. High data rates allow the nodes to spend less TOA although it makes the link fragile.

Nodes located in open-space areas also gave good performance provided their distance from the gateway was short. They were able to alternate between different data rates using ADR by changing SF.

The nodes having close by obstacles in between the link had their performance attenuated, those with a single building were not impacted that much. However, those with multiple building in between had a significant performance effect. Moreover, the hill we saw in between the link for building-39 showed that hills attenuate the signal more than any other obstacle present around the campus.

5.5.2.5 Reliability

We measured the reliability of the network by comparing the packet delivery ratio (PDR) with the packet error rate (PER). Using Table 5.3 we can see that the network performed well in terms of making sure that the packets are received by the gateway.

5.6 Discussion

This subsection presents the discussion of the results and findings presented in Section 5.5. Most discussions of the results were presented along with the analysis. Therefore, this subsection aims to present an overview, clarity, and summary of the results findings above. It must be noted that LoRa is a wireless network based on a selectivity concept for wireless networks; hence, it is important to study its performance behaviour against the environment of deployment.

5.6.1 Lab Experiment Results Discussion

The node experiment section presented a novel LoRa based full-stack sensor node for IWSN, that integrated all the main components on a single board, following the SoC design for energy conservation. As state-of-the-art node designs suggest that node should have external or on-chip energy harvesting source, WaterGrid-Sense employs a solar panel to harvest energy and recharge the battery source that powers the sensor node. The subsection is based on the study presented in Chapter 3.

We conducted two experiments, 1) power consumption of the sensor node 2) communication reliability provided by the sensor node. The results show that without the external energy harvester the sensor node can operate for three months on a battery until cut-off voltage, which is 3.2 V. This means the battery is not completely exhausted but it goes down to a point where the remaining power is below the required power level to operate the sensor node since the voltage regulator utilized output 3.3 V. However, with the use of solar power as an energy-harvesting source the lifespan of the sensor node is extended for as long as the node is exposed to sunlight, only maintenance is required when the server shows faulty signals. In terms of communication reliability, the sensor node produced outstanding results. As we conducted the investigation with the sensor node located indoors communicating with an outdoor gateway. The gateway was located at the mountain; however, the environment remained harsh as it consisted of trees and buildings. During the period of the test, most of the data were received at the server side; though the RSSI fluctuated between low values, the received signal was still sufficient for reliability.

5.6.2 Network Results Discussion

To get an overview performance, reliability and effectiveness of the nodes we started by comparing the furthest node with the closest node in regards to the gateway. As expected, the comparison favoured the closest node with regard to RSSI and SNR. The SF, on the other hand, showed that the nodes had the same behaviour until after some time the furthest node started alternating between different data rates using ADR. Although the closest node disconnected from the network, we assume it would have changed its behaviour as well after the mLinux OS update.

We also discovered that the update had improved the network performance in terms of introducing ADR to the nodes that were not able to use it initially. The nodes that were in a state to use ADR, for instance, nodes deployed in an open space were not utilizing this feature. Moreover, the update changelog can be found here [91]. Along with our observations, we found some nodes that had bad link quality disconnecting from the network after the ADR.

Further investigations after the ADR showed that these nodes had huge variations of data rates. This behaviour was common among the nodes that disconnected. Therefore, in future work, we aim to classify this kind of behaviour and investigate how it causes the nodes to disconnect.

The ADR also causes huge variations on RSSI; this behaviour appeared to cause usage of high load (usage of slow data rates) on the nodes, for which at this point, we assume, to be the reason why some nodes disconnect from the network, especially those nodes that had bad link quality. Authors in [92] investigated the ADR and in their investigation found that the ADR has a potential to impose a load on the nodes due to data rate changes and affecting both the network performance and the node lifetime. In their work, they proposed a fair adaptive data rate that increases the node lifetime and increases network performance by allocating data rates across all the nodes on the network in a fair manner instead of prioritizing some.

In the first analysis where we found long RSSI peaks, authors in [93] suggest that the peaks are due to a temporary multi-path fading effect of the environment especially industrial sites like the CSIR campus. Moreover, we also found that the change in data rates caused significant RSSI peaks which might result in RSSI shifting to either lower or higher values. These results are the same as what authors in [94] found in their research work.

The use of lower values of SF (high data rates) like SF7 make the links fragile to external noise, which causes a huge impact on the performance of both SNR and RSSI. Although, usually the nodes that use SF7 are those close to the gateway or are those located in an open space. The ADR helps to increase the link quality by adjusting the parameters for transmission. The effect then becomes compromising of the SNR and RSSI best performance by slightly giving lower values.

The nodes having obstacles blocking their links used SF12 throughout their lifetime regardless of their distances with regard to the gateway. This includes nodes closer to the gateway, our observations show that although the usage of the SF12 present demanding link profile, the RSSI was not impacted for those nodes, and the SNR was also good i.e. the node at building-37 as seen in Table 5.3. It should be noted that this node had a single building blocking the link.

The findings showed that different obstacles have different impacts on the SNR; vegetation has the least effect while buildings and hills have a significant impact. Although there are more buildings and vegetation across the campus, the link for the node at building-39 had to go through a hill and we observed a substantial impact on the SNR performance as compared to that caused by the buildings, distance, and vegetation. Consecutive buildings in front of the nodes affect the SNR and RSSI significantly especially when the range is of a long distance.

The distance scenarios showed that indeed the distance has an impact on both RSSI and SNR. The RSSI, however, is more affected by the distance than the SNR. The results showed that the two metrics correspond, the more the RSSI values decreases the lower SNR values are observed mainly because the more signal travels over space towards the receiver the more it gets exposed to the noise the link gets impacted and yield lower SNR. In addition, in contrast to long distances in short distances RSSI is not impacted greatly. For short ranges with obstacles in between, the SNR gets affected more than the RSSI although the SNR ends up dragging the RSSI lower.

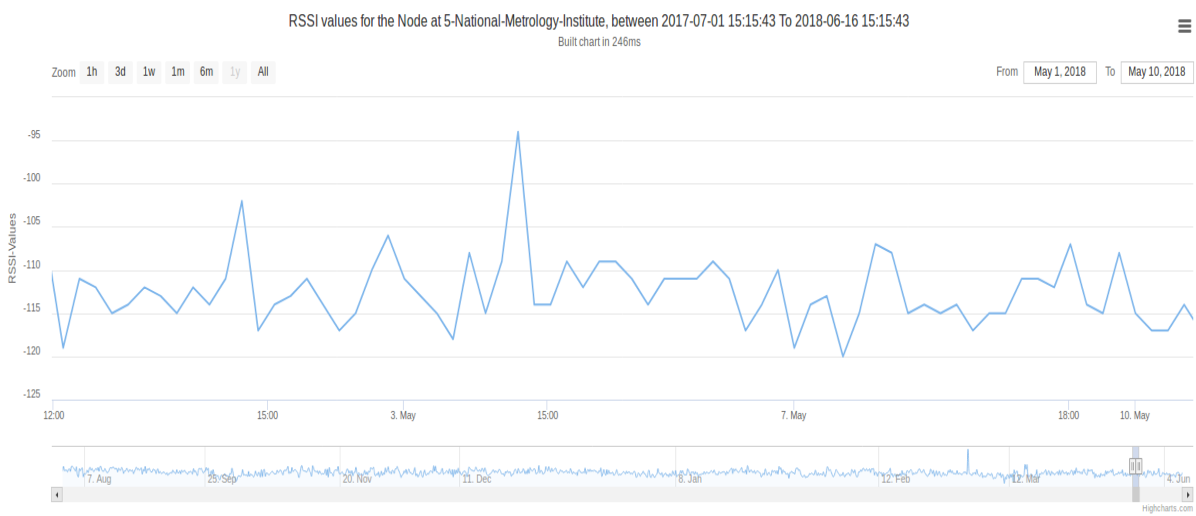

Figure 5.66: Nodes disconnecting from the network due to lack of sunlight

We further investigated the nodes that connected from the network to understand the cause for their disconnection. Our investigation showed that when the nodes reach the cut-off operational voltages presented on the node power-consumption analysis (5.5.1), they disconnect. They reach the cut-off voltage whenever the solar source attached to the node is not charging up the battery. The reason why the solar could not charge the battery to prevent it from reaching the cut-off voltage was due to a lack of sunlight. The nodes that are located where the sunlight cannot reach are the ones that disconnected from the network. Moreover, those nodes that had poor link quality and located in shady locations ended up not reconnecting to the network i.e. node at building-37. Figure 5.66 shows that the node at building-5 disconnected and reconnected to the network during the beginning of May 2018, during the dates 2, 4, 5, 6, 8, and 9 the node was not connected to the network. Lastly, tracing back we can confirm that it was cloudy during those days. Lastly, the lowest RSSI value achieved in the network was -131 dBm. Therefore, we conclude that for our network this value is the receiver sensitivity threshold.

Table 5.4: Overall performance of the test scenarios

Scenario	Communication profile	RSSI (dBm)	SNR (dB)	SF
Distance	Cluster-3:	(-108.29) to (-95.02)	(0.19) to (6.53)	(9.26) to (12.00)
	Cluster-2:	(-111.42) to (-86.79)	(-2.53) to (7.95)	(7.91) to (12.00)
	Cluster-1:	(-108.73) to (-89.03)	(0.64) to (7.76)	(8.37) to (11.57)
LOS	LOS	(-106.47) to (-86.79)	(2.00) to (7.95)	(7.91) to (12.00)
	NLOS	(-111.42) to (-95.02)	(-2.00) to (6.53)	(8.41) to (12.00)
Obstacles	Trees	Less impact	Less impact	Less impact
	Buildings	High impact per	High Impact	High Impact
	Hills	High Impact	High Impact	High Impact
others	Software Updates	Improved	Improved	Improved
ADR		Impacted	Impacted	Improved

Network Nodes Lifetime

The nodes' lifetime forms part of the effectiveness and reliability of LoRa networks. By the time the analysis results were collected for this work, we surveyed how many nodes were still connected to the network. The majority of the nodes were still connected and seven nodes presented in Table 5.5 were still online.

After a full year of the DVT running, we observed that only 9 nodes on the network were fully functional and 22 nodes had problems. Some nodes had power resets, which means for some time they were disconnecting and reconnecting to the network due to power failure. The application on the server however required the nodes to be in sync with the server in terms of time and water meter readings. Some nodes were off due to a lack of sunlight to recharge the battery through the solar panel. Lastly, others were found to have hardware failures, for instance, the voltage regulator on the board had burnt out.

Table 5.5: Lifetime of the disconnected node by the time of data analysis

Node	Lifetime
Building-3B	25 July 2017 to 12 April 2018
Building-5	25 July 2017 to 7 May 2018
Building-8	3 October 2017 to 31 December 2017
Building-12A	3 October 2017 to 25 February 2018
Building-20	3 October 2017 to 5 October 2017
Building-37	3 October 2017 to 24 October 2017
Building-42	25 July 2017 to 24 November 2017

5.7 Chapter Summary

This chapter advanced from the previous chapter by successfully presenting the implementation of the methodology followed. We implemented the DVT and used its generated graph to perform our analysis. We successfully experimented on the WaterGrid-Sense performance and studied its lifetime. We found out that LoRa performs well for Indoor to Outdoor deployments. For the actual network, we discovered that LoRa as a dynamic network can yield unexpected behaviours for different scenarios, for instance, the performance of LoRa networks is influenced by almost all the factors involved.

CHAPTER 6
Summary, Conclusions and Future Work

6.1 Chapter Overview

This chapter provides a detailed summary of this research work. In brief, this chapter will give a summary of the key points of the work. It will also provide reflections on work done, lessons learned, overall insights, and briefly state research contributions. The conclusion for this research work will be presented. Finally, possible future work will be provided.

6.2 Summary

This subsection gives a summary of this work while showing and discussing in general, how each research question was answered, and how the objectives were met. In addition, the methods followed are also presented. In this research work, we presented a study of LoRa combining it with its protocol LoRaWAN. The goal of this work was to contribute to addressing the lack of thorough investigation of LoRa since it is still a new technology. First, as part of the methodology, we identified the gaps in the literature, in order to shape the direction of our work. The gaps found were that most literature works used a limited number of nodes when experimenting on LoRa networks, the investigations were conducted for very short periods of time, and the investigations were not part of real world systems and some were only simulated works. Lastly, LoRa platforms were lacking, most manufacturers are focused on producing only LoRa modules, hence a need to develop a generic monitoring and control platform based on LoRa that can be used across different domains and various applications.

This research compared to others presented long-term results analysis. The data were collected for a year. Moreover, the data were collected from 34 nodes operating in a real deployment of the water management system. To answer our research questions and meet our objectives, a methodology was developed. The research questions **RQ1, RQ2,** and **RQ3** were answered as follows: in order to answer **RQ1**, a complete understanding of LoRa and LoRaWAN was essential. To this end, we conducted a system and requirements analysis presented in CHAPTER 2 and CHAPTER 3 via comprehensive literature review and analysis. The study looked at different LPWANs, their pros, and cons. We further focused on LoRa and explored the type of applications deployed using LoRa as well as the devices used in such networks. In addition, the study was able to identify important LoRa performance metrics which are the

RSSI, SNR, SF, PDR and PER. These metrics are key to evaluating a system in harsh environments.

Since we employed a custom node device in the network, it is important to understand better, how the node is designed and how it works. The node designs and performance play a big role in LoRa networks, certain design guides must be considered. In this study, we used a LoRa based sensor node WaterGrid-Sense. A study of sensor node designs was conducted using literature, this analysis and study was presented in CHAPTER 3 and contributes to answering both **RQ1** and **RQ2**. Furthermore, WaterGrid-Sense design, architecture, functions, and operations, were presented. In addition, we carried out a two-day lab investigation to test the lifetime of the node when operating on battery alone, without external energy harvester and study the network load behavior of the node while in operation.

In order to use the identified metrics for our analysis, the research methods presented in CHAPTER 4 fully answered **RQ2**. We outlined the application we developed to collect and visualize the data collected from the network. We discussed the nature of the environment and how the performance of the network could be hindered by these factors. The structure of how our LoRa network packets were presented is clearly outlined. We developed the test scenarios to be followed on analyzing the data and finally evaluating the effectiveness of the network. Finally, CHAPTER 4 and CHAPTER 5 answered **RQ3**, in CHAPTER 4 we presented the test scenarios that can helped us carry out the analysis that can help us identify the gaps existing on LoRa deployments. Lastly, CHAPTER 5 presented the implementation of the data visualization tool, the results, and the discussion were presented from the analysis and evaluations conducted in order to discover insights from the collected data and identify the research gaps.

6.3 Conclusions

This work aimed to add value and realization of LoRa as a capable communication technology for real world IoT applications. To achieve this, the behavior of the network was observed over an extended period of time as compared to works in the literature. Moreover, many nodes were used which were installed in different environmental settings and different distances allowing the various scenarios. Based on these, several findings were made which constitute the results of this research study.

The first results presented were from the laboratory investigation conducted over two days to study the node lifetime and the behavior of the load on the device while in operation. The results showed that our device, WaterGrid-Sense is able to last for approximately two months, operating only on the battery without any external energy harvester. Although, the LoRa module utilized indicated that the battery could last up to 10 years. The sensor node designs study conducted revealed that the lifetime of the nodes also depends on how the node is designed. On the network, all the nodes, however, use a solar panel as the external energy harvester. The node while in operation had three states, the transmission state (Tx), the idle/reading state, and the sleep state. The results showed that during Tx the node draws a current amount of 0.52 mA, during the idle state 0.16 mA and for sleep state 0.1 mA is drawn. These results in our context are acceptable and correspond to works found in literature.

LoRa is suitable for indoor to outdoor deployments. Our results showed that LoRa is reliable for such scenarios, the PDR was 99.42%; SNR gave a positive average of 4.7 dB; the average RSSI resulted to -101.69 dBm. Using the threshold for the LoRa receivers, which goes to as low as -134 dBm, the difference from our results promises reliability. Looking at the average SNR and considering the scenario, the value is good. The average SF was 12, because of the node being deployed indoors. The reliability and effectiveness of our LoRa network came with a cost of network resources attached to it. On the lifetime of the sensor nodes, most nodes ended up disconnecting from the network because of a lack of sunlight for recharging the battery with the solar panel, keeping in mind that the regulator output on the node is 3.3 V and the cut-off voltage as investigated was 3.2 V. We also found out that sensor nodes sometimes disconnect from the network for days and then reconnect. This state is referred to as a reset-state, as once the node comes back online it restarts all the manually configured setting on the device, this includes parameters such as the time, the water meter reading etc. This becomes a problem when some values have to be configured manually into the node, especially when the node reads analog data. The nodes are able to reconnect to the network when the solar panel has charged the battery above the cut-off voltage. We found out that the load on the node plays a bigger role in depleting the power; this is to say the data rates used by the device. The nodes that had variations of the SF values had affected both the RSSI and the SNR values. The effect of these network metrics affect the performance of the network. Hence, the nodes had to resend the data in most cases. Lastly, the FEC feature that comes was used to correct the packets errors through additional overhead.

The nodes having obstacles blocking their links used SF12 throughout their lifetime regardless of their distances with regard to the gateway. The use of SF12 is always chosen by the LoRa Network Server (LNS), when there is interference to increase link robustness, especially when the link is from buildings and hills, as for trees the SF is able to alternate. For the network results, we expected the clusters to have some form of a decline in performance when the distance between the nodes and gateway extends. However, that was not the case. This shows that LoRa is a dynamic network thanks to the ADR different link profiles can be catered for. The findings show that over time the SNR and RSSI correlate, however, they are affected by different factors, the RSSI gets affected more by the distance while the SNR gets more affected differently by different kinds of objects. The hills have a great impact on SNR values.

6.4 Recommendations and Future Research Directions

6.4.1 Recommendations

The ability to have collected the data from the network for a year allowed us to discover useful information that could not have been possible when observed over a short period. Highlighted below are some recommendations for harsh deployments that have similar scenarios from this work. The goal was to achieve reliability and effectiveness for using LoRa in harsh environments.

- Before deployments, the nodes should be tested and studied, to realize if they can last for a long time in the field without going offline and the need for a change of battery. Although LoRa promises 10 years of battery life, different sensor nodes require different power levels to operate due to the electronic components involved.
- Depending on the purpose of the network, optimal settings should be used to preserve node energy. In this study, the use of ADR has been found to be both advantageous and disadvantageous. ADR causes variation of data rates, and data rates for LoRa correlate with almost all the network factors as shown in the results. Slower rates introduce robustness and introduce packet errors to the links, which can be corrected using FEC however; this option is energy hungry and requires more network resources.
- For reliability FEC should be enabled, for effectiveness, links should be evaluated and decisions to enable ADR and FEC can be taken, links that are less demanding, such links with short distances and LOS, can have default data rates configured and ADR disabled.

- Placement of nodes should be chosen carefully if obstacles are blocking the links, it should be noted that the node would require more network resources for reliability and effectiveness. Nodes behind buildings require exhaustive communication parameters.
- If solar energy is utilized as an external energy harvester, the node should be placed where the sunlight is reachable. In this study, we have found nodes dying because of a lack of sunlight to recharge the battery.
- LoRa is still new and under development. It is important to keep LoRa networks updated in terms of software running them. In this study, we had found that the update of the LoRa NS had enabled the ADR to dynamically adjust communication for the network links.

6.4.2 Future Research Directions

To increase the adoption of LoRa in the future, there is a need for research and development of generic monitoring and control platforms based on LoRa that can be used across different domains and various applications. The use of FPGAs is becoming popular for dynamic systems. The advantage of these processing units is that they can be reprogrammed for different applications. The design of low powered sensor nodes based on FPGA's would provide flexibility for wide usage across IoT applications.

The ADR provided by LoRa is still in question as it imposes variation of transmission parameters, causing different operational load on the network nodes, which results in inconsistent behaviour, which affects the node's communication performance and battery lifetime. More consistency algorithms in terms of ADR should be researched and developed. The use of FEC provided by LoRa should also be investigated in order to explore how the overhead it provides for reliability affects the health of the network nodes. In order to avoid deployment failures for LoRa networks, more research for different network deployments scenarios is lacking. The knowledge for their behaviours can save a lot of time and money used for creating testbeds before real deployments. The use of machine learning in LPWAN's, in general, is also still open for research. These algorithms can be used for anomaly detections in such a network, and to discover more insights about the behavior of these networks. For instance, in this study, we have found LoRa to be a dynamic network through the influence of the environment of deployment. Using machine learning, we can learn to classify these behaviors, in turn making it easy to choose optimal network settings and parameters for different deployments.

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