LORA PERFORMANCE AND ITS PHY LAYER PARAMETERS IN 915MHZ ISM BAND IN INDOOR ENVIRONMENTS

by

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Dedicated to my loving family

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LIST OF ABBREVIATIONS

LPWAN	Low Power Wide Area Network
IoT	Internet of Things
LoRa	Long Range
ISM	Industrial Science Medical
ETSI	European Telecommunications Standards Institute
FCC	Federal Communication Commissions
PHY	Physical
RF	Radio Frequency
MAC	Medium Access Control
RSSI	Received Signal Strength Indication
RPR	Received Packet Ratio
SNR	Signal-to-Noise-Ratio
LoRaWAN	Long Range Wide Area Network
M2M	Machine-to-Machine
CSS	Chirp Spread Spectrum
LAN	Local Area Network
IP	Internet Protocol
SF	Spreading Factor
BW	Bandwidth
CR	Coding Rate
TP	Transmission Power
QoS	Quality of Service
LoS	Line-of-Sight
NLoS	None-Line-of-Site
RX	Receiver
TX	Transmitter
RPR	Received Packet Ratio
BR	Bit Rate

ABSTRACT

Low Power Wide Area Network (LPWAN) is a generic term for a group of wireless network standards such as Sigfox, NB-IoT, and LoRa. LPWAN technologies describe distinguishing key characteristics of wireless communication, such as long battery life, wide area communication, low cost, and limited size of data rate.

In traditional wireless communications, it requires high transmit power in order to achieve long-distance communications. On the other hand, LPWAN technologies send data over long distances requiring a relatively small transmit power. It is possible because the size of the data is minimal. Other characteristics of LPWAN are network security and capacity. Due to these characteristics, LPWAN technologies are becoming one of the fastest developing wireless networks for the Internet of Things (IoT) solutions. Among the LPWAN standards, LoRa, an acronym of Long-Range, has gained lots of attention from many different fields.

LoRa uses license-exempted ISM bands, which refers to Industrial, Science, and Medical bands. ISM bands are open frequency bands and free to use. However, available frequency bands vary from region to region depending on different requirements and regulations defined by regional technical committees. For example, LoRa operates in 868MHz bands in European regions, following the regulations defined and managed by the European Telecommunications Standards Institute (ETSI). In the United States, LoRa operates in 915MHz frequency bands regulated by Federal Communications Commission (FCC).

Many studies conducted LoRa experiments in European, Middle Eastern, and Asian regions. Most studies have focused on the measurements of LoRa performance in outdoor scenarios such as open-space areas, urban cities, marine, and forestry environments. Few studies in indoor environments showed LoRa performance of its communication range and signal strength.

This study aims to evaluate Lora modulation technology by investigating its radio signal quality and reliability as a function of physical factors in indoor office environments at different distances. The measurement metrics used for the performance evaluation of LoRa technology are Received Packet Ratio (RPR), Received Signal Strength Indication (RSSI), and Signal to Noise Ratio (SNR).

CHAPTER 1. INTRODUCTION

This chapter provides an overview of this thesis study. It first introduces the background of LoRa. In the following section it explains the problem statement. Section 1.3 proposes the research question, followed by three more parts that note research significance, purpose, and the summary of this chapter.

1.1 Background

In recent years, the evolutionary development and growth of sensor and wireless network technologies have enabled advanced connections among things, machines, and people. According to Cisco Annual Internet Report, within the Machine-to-Machine connections category, the Internet of Things (IoT) home applications will have nearly half or 48 percent of M2M share by 2023 (Cisco, 2020).

The term Internet of Things, which also refers to Machine-to-Machine connections, has emerged and become popular ever since Kevin Ashton brought it up at Procter and Gamble during his presentation in 1999 (Ashton, 2009). In the early stage of IoT wireless communications, networks in the form of mesh topology were dominant. However, this type of network, such as ZigBee, has drawbacks of small communication range and high data rate. On the other hand, Low Power Wide Area Networks (LPWAN) enable wireless connection over long distances. In early 2013, the term Low Power Wide Area (LPWA) did not even exist (Semtech Corporate Whitepaper, 2015). LPWAN includes technologies such as Sigfox, NB IoT, LTE-M, and LoRa.

LoRa is a radio modulation technology patented by Semtech (Semtech, 2019). LoRa technology is well known for wide communication coverage. Due to its outstanding operation over long distances, many studies have focused on LoRa and LoRaWAN performance in outdoor environments. LoRa is a proprietary **spread spectrum modulation** scheme derivative of **Chirp Spread Spectrum modulation** (CSS), exchanging data speed for better sensitivity within a fixed channel bandwidth (Semtech Corporation, 2015). One of the traits of CSS is its robustness against interferences. With this, LoRa modulation provides immunity to multipath fading due to its broad-spectrum shape, enabling LoRa to achieve long-distance communication coverage. Therefore, it is ideal for use in both urban and indoor environments (Semtech, 2019).

Most IoT sensor monitoring devices generate a small data size, and LoRa's wide-area communication is available with a limited size of data. Therefore, LoRa wireless radio signal for data communication is applicable in both indoor and outdoor IoT scenarios.

According to Semtech (Semtech, 2019), LoRa is expected to perform IoT network applications in many different environments: agricultural, industrial, rural, sub-rural, urban, and suburban. Some studies experimented LoRa performance measurements in outdoor open areas (Yim et al., 2018; Ko et al., 2018), dense urban areas (Callebaut & Van der Perre, 2020; Thu, Htun, Aung, Shwe, & Tun, 2018; Yousuf, Rochester, Ousat, & Ghaderi, 2018; Villarim, de Luna, de Farias Medeiros, Pereira, & de Souza, 2019), and few studies in indoor environments (Haxhibeqiri et al., 2017; Ameloot, Torre, & Rogier, 2018; Wang et al., 2018).

It is also noticeable that most LoRa studies were conducted in European regions where LoRa operates in the 868MHz frequency band. In North America, LoRa uses 915MHz frequency bands.

1.2 Problem Statement

LoRa technology, among LPWAN technologies, has gained much attention from academic and industrial researchers with its beneficial traits for IoT applications. Many of LoRa and LoRaWAN studies for performance measurement have been conducted in various environmental scenarios: city (Callebaut & Van der Perre, 2020; Thu, Htun, Aung, Shwe, & Tun, 2018; Yousuf, Rochester, Ousat, & Ghaderi, 2018; Villarim, de Luna, de Farias Medeiros, Pereira, & de Souza, 2019), campus (Wang et al., 2018), forests (Bianco, Giuliano, Marrocco, Mazzenga, & Mejia-Aguilar, 2020).

However, there still are challenges in developing practical LoRaWAN IoT application systems. For example, many existing studies focused on the challenges of reliable transmissions in outdoor environments. Nevertheless, very few practical works have measured LoRa and LoRaWAN performances regarding signal strength and reliability in indoor environments. Furthermore, most of those studies focus on evaluating the maximum distances.

In wireless communication, link budget will degrade by the effects of diffraction, refraction, reflection, and scattering, which are promoted by various types of interference such as other RF signals and noises, and other obstacles such as walls, buildings, vegetation, hills, and many other daily obstructors, or environmental factors such as temperature and humidity.

Even if there are a lot of previous studies of LoRa and LoRaWAN, few studies exist for performance measurement of LoRa radio performance, especially in indoor spaces. Moreover, there are not enough studies of LoRa radio signal measurement with real-world applications. Most of the evaluation studies have been conducted in simulations.

Lastly, many studies are done in European regions where LoRa is available in 868MHz ISM bands. In the United States, LoRa is available in 915MHz ISM bands.

Therefore, in this paper, the LoRa radio modulation technology is studied with real-world measurements in different parameter settings in different distances of indoor office spaces in 915MHz ISM bands.

1.3 Research Question

This research focuses on answering the following question:

- How do different configurations of LoRa physical layer parameters - spreading factor, bandwidth, and coding rate - affect the quality of LoRa performance, operating on the 915MHz ISM band in indoor office environments?

1.4 Assumptions

Below are the assumptions of this study:

- Hardware specifications provided by the manufacturers are reliable information.
- The software library and tools used in this study perform properly.
- The experiment is conducted with utilizing available resources and materials.

1.5 Limitations

Following are the limitations of this study:

- The research experiment follows the U.S. Federal Communications Commissions (FCC) regulations.
- This study is limited to be conducted in Purdue West Lafayette Campus buildings in Indiana, the United States of America with access permissions granted for a security reason.
- LoRa performance is tested with the use of Dragino LoRa shield and Arduino Uno.
- There are other signal interferences by various sources in the testing environments.

- Room temperature and humidity cannot be controlled for the testing process.

1.6 Delimitations

The delimitations of the research are listed below:

- This study is not sponsored by any commercial retailers.
- The research is only carried out in indoor environment.
- At each testing period, two end nodes (LoRa TX and LoRa RX) are communicating.
- The impact of multipath on LoRa modulation is not considered to be discussed in this study.
- This study does not take energy consumption into account.

1.7 Significance

According to the whitepaper from Semtech (Semtech Corporate Whitepaper, 2015), it is expected that there will be 3.6 billion LPWA connections by 2024. Increasingly IoT applications and wireless connections are being implemented not only in outdoor environments in many different forms of environmental spaces such as smart cities, smart buildings, smart factories, and more. LoRa is known for its long-range communication and its robustness against inferences with the benefit of using chirp spreading spectrum. However, few works have been found to study the link performance of LoRa/LoRaWAN in indoor environments where diverse types of obstructors can affect the link performance. Also, evaluation on the impact of PHY settings for effective data rate with reliable signal strength is necessary to be studied since IoT application developers can fine-tune PHY settings to select more effective network communication performance.

Therefore, it is necessary to provide more work in various parameter settings in indoor scenarios. Practical LoRa experiments in the type of indoor environment will be able to provide helpful information about its indoor performance for further academic and commercial researchers who consider the implementation of LoRa and LoRaWAN.

By collecting and analyzing packet-sized messages using real-world LoRa end devices, this study expects to provide helpful insights to observe how LoRa signals perform with different LoRa physical parameter settings in indoor spaces.

1.8 Purpose

The term LPWA did not even exist by early 2013 (Semtech Corporate Whitepaper, 2015). Amoung many IoT-related technologies, wireless communication technologies have received enormous attention. It means that the market for wireless networking technologies is growing fast. Therefore, LoRa, one of the most popular wide-area wireless communication technologies, needs more practical experimental studies with its performance comparison in different environments to facilitate its network planning and coverage prediction. In many existing works, studies focus on the performance measurement of LoRa signal strength over various distances. However, it is a known fact that the performance of LoRa, much like typical radio waves, decreases over longer distances. In this study, the researcher focuses on finding the answers to the research question represented in section 1.3, which is “How do different configuration settings of LoRa physical layer parameters - spreading factor, bandwidth, and coding rate - affect the quality of LoRa performance, operating on the 915MHz ISM band in indoor environments?”

1.9 Summary

LoRa commercial chips were released in 2015. LoRa and LoRaWAN is a relatively new area of wireless communication technologies in academic and industrial studies. Most of the works have been conducted in European regions. How LoRa/LoRaWAN performance evaluation in various environmental scenarios has been an active research topic for researchers, and there are many existing works carried out in outdoor scenarios. On top of that, it is necessary to study how LoRa/LoRaWAN performs in indoor environments as one of the fast-growing IoT network mechanisms. However, few studies are found to work on LoRa and LoRaWAN performance evaluation in indoor scenarios. Furthermore, since LoRa technology is known for its cost-effectiveness, it would be significant to conduct a real-world experiment to understand how LoRa radio signals behave according to its physical layer parameter settings.

In order to answer the research question, statistical interpretation of the testing results is provided interpretation in chapter 4 (Result) and chapter 5 (Conclusion).

CHAPTER 2. LITERATURE REVIEW

This chapter is divided into three parts. In the first part, it gives an overview of Low-Power-Wide-Area Networks, including its definition and its representing technologies, then provides a brief definition of LoRa and LoRaWAN. The next part provides a literature review of LoRa and LoRaWAN performance evaluation in two types of environments: outdoor and indoor.

2.1 LPWAN

LPWAN stands for Low-Power Wide-Area networks like a cellular network but more optimized for IoT and Machine-to-Machine communications. The architecture is almost the same. There is a network of base stations worldwide, and the end nodes uplink directly to those base stations without meshing or routing among themselves. They shape the form of a star topology, and they range over miles. So, these two types of networks have some similarities except the available amount of data rate.

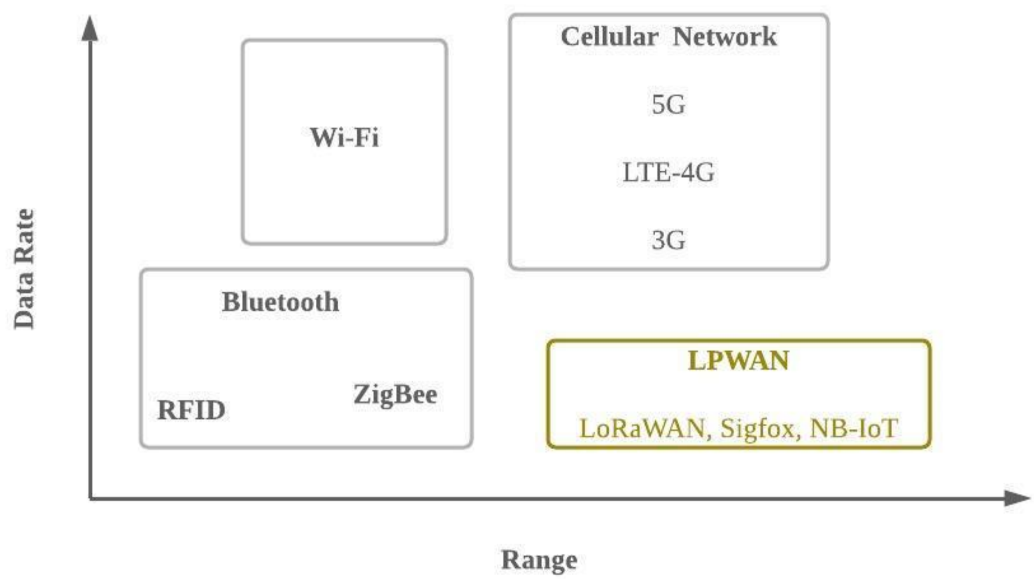

Figure 2.1. Wireless Network Technologies

Figure 2.1 shows common and well-known wireless network technologies. Each of them has distinct characteristics. LAN, which stands for Local Area Networks, are typically short-range wireless technologies such as Wi-Fi and Bluetooth. Even though LAN produces a high data rate and enables fast video streaming in real-time, their battery life is short. Cellular networks, such as the 3rd generation, LTE - the 4th generation, and now the 5th generation, are those that commercial telecommunication companies manage. However, such telecommunication vendors possess their base stations and provide services within their existing coverage. Therefore, they can provide guaranteed quality of services with a high data rate to their customers. Other LPWAN technologies can send small-size data over extremely long distances.

The potential of LPWANs (Low Power Wide Area Network) can unlock the new IoT market by providing low-cost applications with long battery life over long distances. The fundamental characteristics of LPWAN are long battery life, wide-coverage, low cost, and limited data throughput capacity. It is expected that there will be 3.6 billion LPWA connections by 2024 (Semtech Corporate Whitepaper, 2015). Deploying LPWAN services, in terms of the Internet of Things applications, would be beneficial in scenarios such as smart cities, industrial and manufacture systems, agricultural, and other shared services (Link Labs, 2016). There are three communication models to describe how IoT devices connect and communicate.

1. Device to device
2. Device to cloud
3. Device to gateway to cloud

Direct device-to-device connection is called mesh networks such as Bluetooth, Z-wave, and ZigBee. Device to cloud connection makes use of existing communication mechanisms. For example, wireless connections like ethernet or Wi-Fi can be utilized to establish a connection between two devices or IP networks. It is how some commercial voice recognition assistants and smart TVs connect to their cloud servers. However, in terms of IoT networks, those two wireless technologies have some drawbacks. Unlike LPWAN, the other two technologies require wide bandwidth, and they are expensive technologies. One reason for the expensive costs is that these two wireless networks transmit large-size data. Moreover, those technologies consume more power, and some of them have limited communication ranges.

In order to implement IoT applications, many aspects must be considered, including the cost of devices and networks, battery consumption, data rate (throughput), latency, mobility, communication coverage, and deployment architecture. However, there is no single technology that can solve these attributes altogether.

2.2 LoRa and LoRaWAN

Sometimes, it is often observable using LoRa and LoRaWAN interchangeably as the same terminology. Though, disambiguating these two terms, LoRa and LoRaWAN, is necessary since each represents a distinct network layer(s). LoRa is an acronym for 'Long Range,' and LoRaWAN means 'Long Range Wide Area Network.

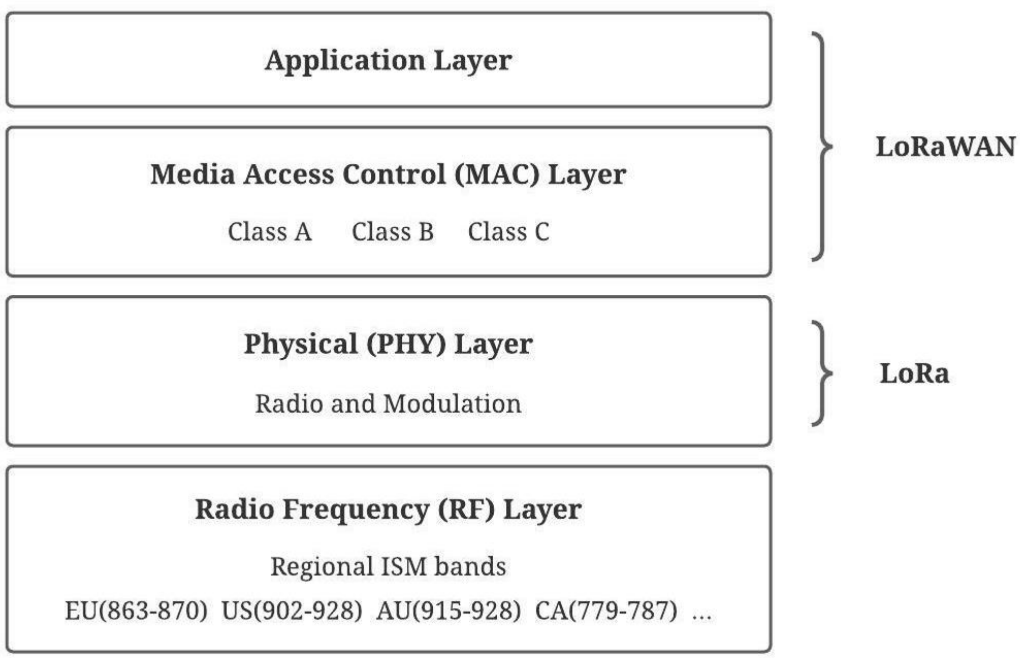

Figure 2.2. LoRa Protocol Stack

LoRa is the physical (PHY) layer of the network standard, and it is a modulation technology developed and patented by Semtech (Semtech, 2019). LoRa uses license-exempted ISM bands. ISM refers to industrial, scientific, and medical bands. They are open frequency bands and free to use but differ from place to place. Moreover, different requirements and regulations for these unlicensed frequency bands are defined and managed by regional technical authorities. For example, in Europe, LoRa operates on 868MHz and 430MHz frequency bands by different regions. In Asia, LoRa is available in 430MHz bands. In the United States, the Federal Communication Commissions (FCC) regulates these ISM bands in 902MHz to 928MHz, and LoRa uses the 915MHz frequency band (LoRa Alliance, 2015). Under the FCC laws in the United States, study results provided in different frequencies cannot be compared locally.

Different from LoRa, LoRaWAN is the upper stack over LoRa. It is a cloud-based MAC (medium access control) layer on top of LoRa. LoRaWAN defines the communication protocol and network architecture that utilizes LoRa physical layer. LoRaWAN is a standard that defines the structure of data packets, how data packets are processed on the server, how data packets are formed, and how messages are encrypted (Raza, Kulkarni, Sooriyabandara, 2017).

In figure 2.2, in the LoRaWAN architecture, the end devices and the gateway communicate through LoRa link. The gateway sends or receives data to or from the cloud server using a standard internet protocol (IP) network.

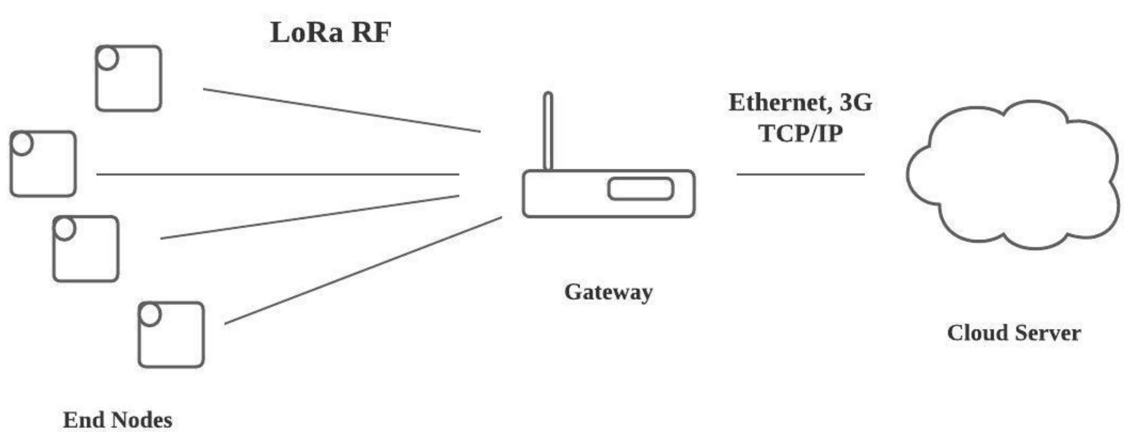

Figure 2.3. LoRaWAN Architecture

LoRaWAN is maintained by this association called LoRa Alliance. LoRa Alliance is a non-profit association established in 2015 to support LoRaWAN protocol with over 500 members such as IBM, Cisco, Telcom, and many more.

2.2.1 Chirp Spreading Spectrum

LoRa utilizes chirp spread spectrum (CSS), a type of spread spectrum technology. With CSS, LoRa modulation technology provides long-range communications and high immunity to interference while consuming low battery power. Chirp spread spectrum is the technology that is optimal for applications that require extended coverage or link robustness.

Chirp spread spectrum technology draws each bit of the payload data by multiple chirps of information. When broadcasting a signal, it applies its entire allocated bandwidth, giving it immunity to channel noise. With CSS technology, LoRa signal is resistant to multipath fading.

CSS was developed for radar applications in the 1940s. Initially, many communication applications for military and security purposes used this technology.

CSS has become commercially available, and Semtech’s LoRa modulation utilizes CSS technology at the physical layer (Semtech, 2019). LoRa modulation achieves the spreading of the spectrum by producing a constantly modifying chirp signal in the frequency. Basically, CSS is what enables LoRa’s strong signal and its long-range communication links.

2.2.2 ISM Bands

Many IoT applications such as remote control, environmental monitoring, sensing is built through wireless links, and most cases use license-free, which means free of charge, RF products in ISM bands. Unlike licensed wireless products, wireless products using unlicensed RF in ISM bands need to follow restrictions by authorized regulatory agencies to avoid signal conflicts. Therefore, it is essential to familiarize oneself and to comply with ISM band regulations.

LoRa operates in the license-free ISM radio bands globally, but ISM band standards and rules differ by region.

In the United States, the Federal Communications Commission (FCC) establishes standards and manages wireless communications regulations. ISM stands for Industrial, Science, and Medical, and in the US, the frequency range of 902-928 MHz is defined for ISM bands by FCC. Therefore, this frequency is often referred to as the '915MHz ISM band'.

Table 2.1. Global License-free ISM Radio Band Frequencies

Region	**Frequency (MHz)**
Asia (parts)	433
Europe, Russia, India, Africa (parts)	864 – 870
US	902 -928
Australia	915 - 928
Canada	779 – 787
China	779 – 787, 470 - 510

2.2.3 LoRa Physical Layer Parameters

The Lora module can be tuned by the configuration of different LoRa PHY parameters. LoRa allows data transmission at an extremely slow transmission speed over extremely long distances. LoRa data rate is calculated with PHY parameters, so it is crucial to understand what PHY parameters LoRa can configure and how they impact LoRa. Moreover, PHY parameters can be tuned to achieve optimal transmission performance in an energy-effective way. This section provides descriptions of four LoRa physical parameters: Spreading Factor (SF), Bandwidth (BW), Coding Rate (CR), and Transmission Power (TP). These PHY configurations can achieve different LoRa performances. Furthermore, LoRa bit rate (Rb) can be calculated with three configurable parameters: Bandwidth (BW), Coding Rate (CR), Spreading Factor (SF).

$$R_b = SF * \left(\frac{BW}{2^{SF}}\right) * CR \qquad (1)$$

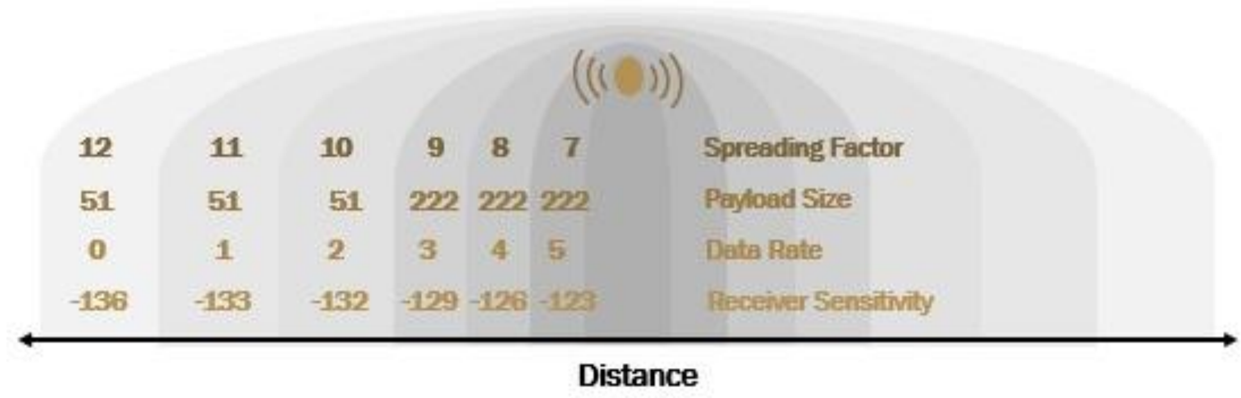

Figure 2.4. LoRa Physical Parameters

1. Spreading Factor (SF)

The spreading factor is the ratio between the bit and chips. It determines the number of raw bits being encoded by a symbol. Therefore, the bigger the SF value is, the more the number of bits in a symbol. Each symbol can hold 2SF chips. Therefore, a higher SF value will put more processing gain from the receiver side, allowing the receiver to receive SNR values under 0. Figure 2.1 shows that the lower the SF value, the higher the transmission data rate, but the available communication range decreases. It is exactly the opposite with higher SF values. LoRa allows SF values from 7 to 12. It is important to note that the LoRa modulation spreading factors are essentially orthogonal, meaning that when the signals modulated with different spreading factors are transmitted at the same time on the same frequency channel, they do not interfere with each other; instead, signals in different spreading factors appear as noise to each other.

2. Bandwidth (BW)

It is the frequency range of the chirp signal used in the transmission band. The higher the BW, the higher the data transmission rate. However, higher BW gives lower sensitivity to noise aggregation. LoRa can operate in 125, 250, or 500KHz. In LoRa, bandwidth is used interchangeably with chirp rate (Rc).

$$R_c = BW \tag{2}$$

3. Coding Rate (CR)

LoRa modulation adds a forward error correction (FEC) in every data transmission. The coding rate is the Forward Error Correction (FEC) rate. It is done by encoding 4-bit data with redundancies into 5-bit, 6-bit, 7-bit or 8-bit. Using this redundancy will allow LoRa signal to endure short interferences. If there is more interference in the channel, increasing CR value is recommended, but a higher CR value will cause more transmission time. It recovers bits of information corrupted by interference. A higher coding rate improves the robustness of radio links.

$$CR = 4/(4+i), \qquad i = \{1,2,3,4\} \tag{3}$$

LoRa allows four coding rates: 4/5, 4/6, 4/7, and 4/8. The smaller the coding rate (the smallest is 4/8), the stronger the signal against noise, but on the other hand, it increases the Time on Air (ToA) and energy consumption. It is because slow data transmission affects more time spent in transmission mode, which involves more battery consumption.

4. Transmission Power (TP)

LoRa transmission power varies from -4dBm to 20 dBm. However, due to some implementation limitations, TP ranges from 2 dBm to 20 dBm (Semtech, 2019). The higher the transmission power, the higher power consumption and SNR.

2.3 Related Works

This section introduces previous studies that conducted experiments for LoRa and LoRaWAN in various types of environments.

In Riparian Forests of three local rivers at urban, semi-urban, and rural environments in Cuenca, Ecuador (Avila-Campos, Astudillo-Salinas, Vazquez-Rodas, & Araujo, 2019), empirical studies of LoRa and LoRaWAN communication range using RSSI and SNR for the performance evaluation metrics. This study made propagation measurements in the 915MHz frequency band, which is allowed in American regions. Many LoRa and LoRaWAN studies in outdoor environments have been done in European regions where LoRa is allowed to use the 868MHz frequency band. This study found that in the forestry areas, the transmission range highly depends on environmental factors.

To develop a path loss model, Callebaut & Van der Perre, 2020 aimed to study LoRa coverage and performance measurements. This work is done using the European 868MHz ISM band in water and coastal environments. In the study, the experiments in urban areas showed that more than half of the data packets were successfully transmitted from 5km to10km distances in kilometers.

A study by Zhao, Wu, & Li, 2019 evaluates LoRa performance with multiple gateways using RSSI and ACKs to estimate the connection rate. In addition, this work evaluated the reliability of LoRa using long transmission periods. In this experiment, more than one gateway was implemented to detect mobile network interference.

Both Yim et al., 2018 and Ko et al., 2018 focused on agricultural use cases in a tree farm. The latter compared the LoRa network performance in the tree farm with its performance in the open area by setting different LoRa PHY factors. The interesting part of these two studies is that they experimented in Indiana, United States. The studies used the 915MHz ISM band in flat open and dense forestry outdoor environments. The two works focus on analyzing the effects of different parameters of the LoRa network physical layer on its performance in a tree farm and comparing those in a tree farm and a LOS (line of sight) open space. Values of spreading factor (SF), bandwidth (BW), and coding rate (CR) were modulated in different settings in the 915MHz frequency band at 13dBm transmit power. In Yim et al., 2018, the study result describes how different PHY factors and distances impact LoRa network reliability in a tree farm. From their experiment results, the LoRa transmission rate did not reach the evaluated values in the specification of LoRa technology. The authors describe that as they expected, physical layer settings followed predictions. Increasing spreading factors and coding rate resulted in higher signal reliability at longer distances. Nevertheless, unlike Semtech's claim, they could not find an obvious relation of spreading factors with the RSSI, but they stated that the RSSI seemed to be affected by distances. On the other hand, the research found that bandwidth seemed to have minimal impact on LoRa performance. However, it was not possible to discover its relationship with configuring bandwidth. Their continuous work (Ko et al., 2018) showed that packet delivery rate (PDR) is more sensitive to PHY factors in the tree farm, and PDR is higher in the open space than in the tree farm.

Another study (Aref & Sikora, 2014) evaluated LoRa technology in outdoor environmental experiments in Germany, where 868MHz frequency is used. Bandwidth and data rate were changed in modulation to test the network performance of LoRa. The study showed that the packet transmission was successfully achieved at the 6km range with the data payload limited to 10 bytes. However, when the data payload of 50 bytes was sent at a 2 km distance, the packet error rate (PER) increased to 10 percent. It is a known fact that LoRa performance decreases as the data range increases. Therefore, LoRa is intended to be applied in IoT systems where it is needed to send small-size data.

According to Wang et al., 2018, which implemented a practical IoT communication in the campus area of National Chiao Tung University in Taiwan, the performance evaluation was investigated with the LoRa-based IoT applications of a real-time long-term use PM2.5 air quality monitoring system. This study aims to build a real-life smart campus air monitoring IoT application. The work showed how packet losses were affected by the distance between end-nodes and the gateway, the payload length, and the weather conditions in indoor measurements over a long-distances maximum of 1,200 meters from a gateway to a sensor deployed in different buildings. Sensors were deployed inside the buildings while gateways were put on the rooftop of different buildings. An end device that achieved a high packet loss rate has a communication distance of 1200 meters. This result explains that the larger the distance, the higher the packet loss rate. Furthermore, for the experiment of packet loss against payload length, the result shows that using a longer payload length does not necessarily increase the packet loss rate in LoRa communication. Lastly, the test of packet loss against weather seems reliable that the weather factor such as rain can significantly increase the LoRa packet loss rate.

In the study by Ameloot, Torre, & Rogier, 2018, custom-built LoRa nodes were implemented to measure the indoor performance of LoRa propagation characteristics for both 434MHz and 868MHz IMS bands, which are not operatable in North America. This work presents a performance test of LoRa in a regular indoor office environment. The customized LoRa sensor nodes send and receive packets in both 434MHz and 868MHz ISM bands. The SNR measurement data on LoRa packets were gathered for performance analysis, and the result shows that the presence of people in the building has a negative impact on the quality of LoRa communication, which means that the presence of people can be seen as a factor that decreases the quality of service (QoS) of LoRa communication. The study concluded that due to the superior propagation characteristics of 434MHz that penetrate through walls better than 868MHz, the 434MHz band is expected for better performance of LoRa communication in indoor environments. However, this is not possible to be tested in North America, where only the 915MHz IMS band is the only available implementation option for LoRa network. The most interesting part of this study is that it seems possible that the existence of people in the building negatively affects LoRa data communication. There are not many experiments that measure the LoRa signal performance in an indoor environment with the existence of people.

2.4 Summary

This chapter provided an overview of LPWAN and descriptions of LoRa and LoRaWAN, and reviewed literature relevant to the LoRa and LoRaWAN performances. The next chapter provides methodologies of data collection and measurement metrics to be used in the research project.

CHAPTER 3. METHODOLOGY

Chapter 3 describes methodologies for data sample collection, hardware description, and metrics for performance measurement. In section 3.1, data collection processes are explained. Section 3.2 provides hardware descriptions of LoRa devices that are utilized for testing. In the following section, a chart of LoRa PHY parameter combinations at each testing phase is presented. In section 3.4, test environments are described with the locations of LoRa nodes. Lastly, section 3.5 discusses two evaluation metrics, RSSI and SNR, used in this study to measure LoRa signal quality from the collected data.

3.1 Data Collection

Data is collected through real-world experiments in a campus environment. The experiments for data sample collection were conducted in September 2021 in the Purdue Campus area in West Lafayette, Indiana, United States. The data transmitted between LoRa transmitter and LoRa receiver is packet-sized (17 bytes) messages. The LoRa PHY parameters are synchronized on both RX and TX nodes due to the reason of using a single channel connection. When the LoRa RX node detects sent packets, it reads the packets through the Arduino serial port and records the data in the spreadsheet. Below is the format of the dataset.

- Time
- Date
- Spreading Factor (SF)
- Bandwidth (BW)
- Coding Rate (CR)
- Packet Size
- Packet RSSI
- Packet SNR
- RSSI
- Distance

3.2 Hardware Setup

With existing available resources, this experiment is conducted with single-channel LoRa client nodes and a LoRa receiver node.

The client-side of LoRa end-nodes perform as the transmitter (TX) that sends LoRa packets to the LoRa receiver (RX) node. In order to measure LoRa signal performances at different parameter configurations, RSSI and SNR are calculated at the receiver node. RSSI is an acronym for Received Signal Strength Indicator. The RSSI values are collected to measure the performance of LoRa radio propagation. Testing nodes are deployed at inside-of-building locations in an urban campus area.

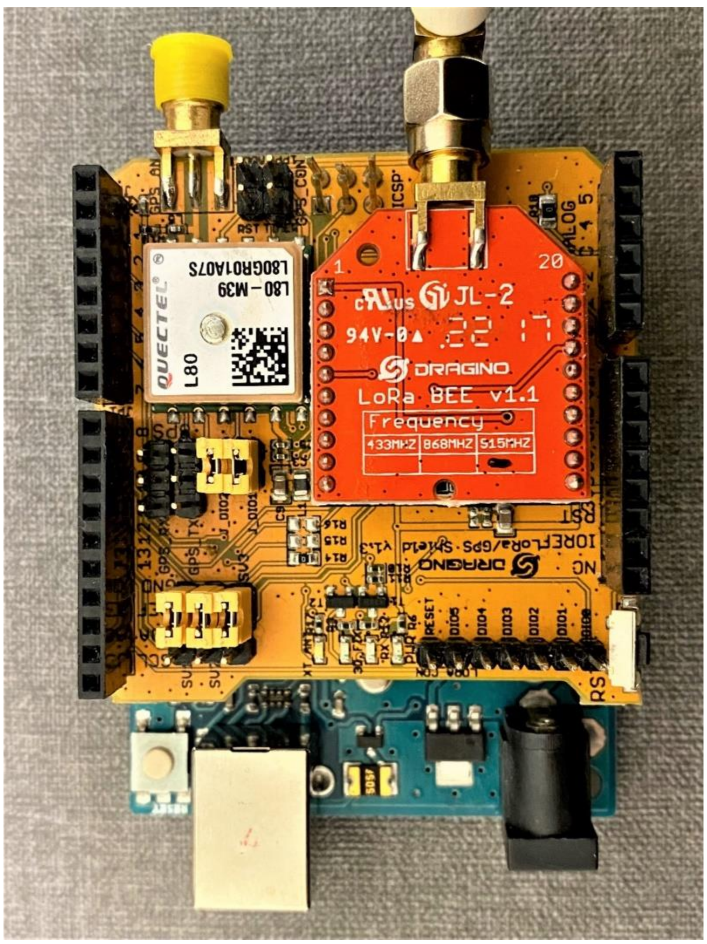

Figure 3.1. Arduino Uno MCU Board with Dragino LoRa/GPS Shield v1.3

When implementing LoRa connections, it is critical to use the same modulation chip on both receiver and transceiver in the same frequency. For this reason, LoRa transceivers with the SX1276 module (Semtech, 2019) are deployed operating in the 915MHz frequency band on both LoRa RX and TX end nodes in this study. The frequency band is pre-configured by manufacturers. Figure 3.1 is a picture of Dragino LoRa/GPS shield version 1.3 mounted on Arduino Uno microprocessor. Dragino LoRa/GPS shield version 1.3 is compatible with Arduino Leonardo, Uno, and Mega.

Figure 3.2 is a picture of Dragino LoRa BEE based on the SX1276 radio transceiver modulation chip.

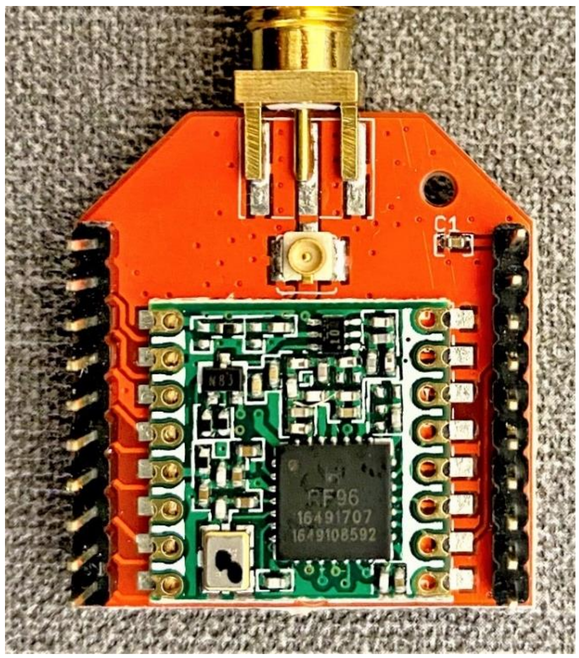

Figure 3.2. SX1276 RF LoRa Module

Table 3.1 describes the hardware features of the SX1276 LoRa transceiver module. The maximum link budget it can operate shows a very high rate. It is also noticeable that this LoRa module gives very high sensitivity, down to -148 dBm, as well as a dynamic range of RSSI. These hardware configuration features give information that the SX1276 module can operate LoRa signals over long distances with excellent blocking immunity against the interference of noises.

Table 3.1. SX1276 LoRa Module Specifications (Semtech,2019)

Component	Hardware Configuration
Maximum Link Budget	168 dB
Maximum Programmable Bit Rate	Up to 300 kbps
High Sensitivity	Down to -148 dBm
Dynamic Range RSSI	127 dB
Packet Engine	Up to 256 bytes with CRC
Module Size	1616 mm
Low RX current	10.3 mA

3.3 LoRa PHY Parameter Configurations

Table 3.2. LoRa PHY Parameter Configurations

Parameter	Configurable Values
TX Power	17 dB*
Frequency	915MHz*
Spreading Factor	7, 9, 11
Bandwidth	125kHz, 250kHz, 500kHz
Coding Rate	4/5, 4/6, 4/7, 4/8
Preamble Length	8*

*Default setting

LoRa can operate with different PHY factors. Three major parameters can be considered in the measurement of LoRa signal performance. They are Bandwidth (BW) and Coding Rate (CR), and Spreading Factor (SF). LoRa supports signal bandwidth in 125KHz, 250KHz, and 500KHz. For the coding rate, there are four values to be considered - 4/5, 4/6, 4/6, and 4/8. When the coding rate increases, signal reliability increases, but the data rate decreases. Typically, LoRa modulation supports six spreading factors, and they are values between 7 and 12. In this study, three spreading factors are considered, which are 7, 9, and 11. Different spreading factors can impact data rate, radio distance, time-on-air, energy consumption, and receiver sensitivity.

Bit Rate

The lower the spreading factor, the higher the bit rate. In other words, SF 7 provides a higher bit rate while SF 12 returns a lower bit rate.

Distance

When a LoRa signal is modulated with a larger spreading factor, the signal travels a longer distance with fewer errors compared to a signal with a smaller spreading factor.

ToA

With fixed payload and fixed bandwidth, a signal with a higher spreading factor takes more time on the air (ToA).

Energy Consumption

The smaller the spreading factor is, the longer the battery lasts for an end device. In other words, an end device's energy consumption is higher when its signal is modulated with a higher spreading factor.

Receiver Sensitivity

SF 12 provides the highest receiver sensitivity compared to SF 7, which provides the lowest receiver sensitivity.

Therefore, LoRa modulation is configured with 36 unique settings of LoRa PHY parameters during the field experiments.

3.4 Experimental Setup

Figure 3.3. Arduino UNO MCU Board with LoRa Module and Battery

For testing purposes, each microcontroller-based unit (MCU) Arduino board is mounted with a Dragino LoRa shield equipped with an SX1276 radio module operating in the 915MHz band and a ½ wave omnidirectional antenna. The LoRa testing devices are placed in two indoor environments: for short-range tests, devices are placed inside the building of Purdue Korean Software Square, and for longer-distance communication, they are installed inside Knoy Hall of Purdue University West Lafayette campus in Indiana in the United States. A portable battery pack powers each testing device.

The testing is organized with machine-to-machine (M2M) communication: LoRa packet transmitter and LoRa packet receiver. The LoRa TX broadcasts packets every three seconds, and the LoRa TX receives them in the NLOS indoor office space.

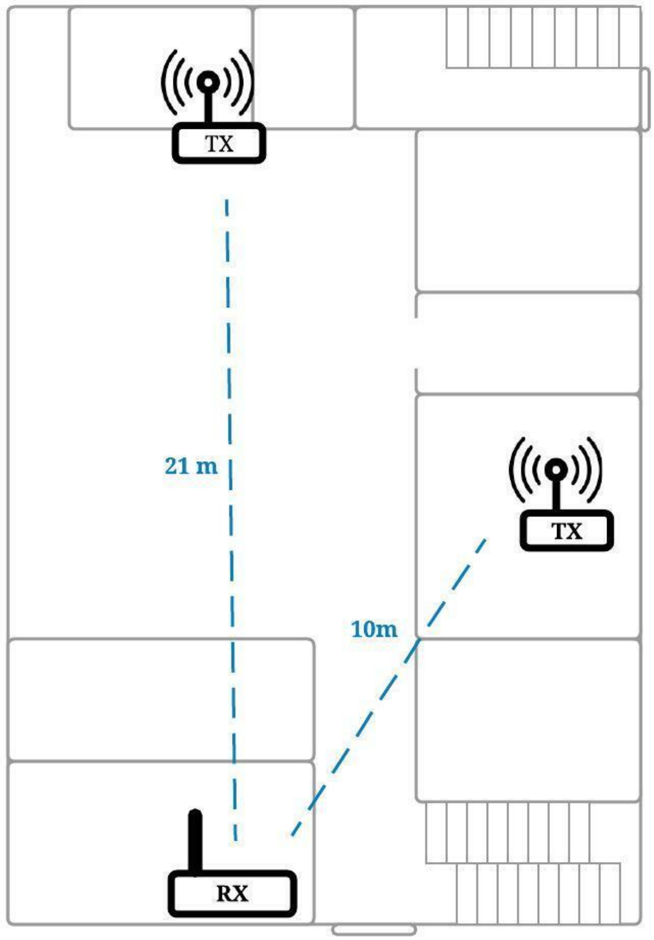

Figure 3.4. LoRa TX and RX Node Placement in Inside the Purdue Korean Software Square Building.

LoRa wireless link performance is measured in the none-line-of-sight (NLOS) indoor office spaces with building constructional obstacles between the LoRa TX and RX end-devices at different distances.

Figure 3.4 shows the LoRa end node setup plan in the indoor space of Purdue Korean Software Square building in West Lafayette. At each experiment, LoRa TX end devices are placed 10 (±0.5) meters and 21 (±1.5) meters away from LoRa RX end device, 1 (±0.1) meter above the ground level on the first floor of the building. In the same manner, testing nodes are deployed 40 (±1.5) meters away for the longer distance field testing. Each field testing is conducted at a separate period.

3.5 LoRa Link Performance Evaluation Metrics

The RSSI and SNR are measured to characterize the communication link between Lora communications. The Received Signal Strength Indication (RSSI) and Signal-to-Noise Ratio (SNR) are two physical level indicators available on wireless radio chips.

The RSSI has negative values in dBm. Typically, the RSSI is used as a measurement metric of radio signal strength to assess how well a receiver can hear a signal from a sender. As the RSSI value gets closer to 0, it means that the radio frequency obtains strong signals.

Signal-to-Noise Ratio (SNR) is a figure that indicates the ratio between the received power signal and the level of noise floor power expressed in dB. The noise floor is where interfering signals, also known as noises, exist. Noise floors degrade the transmitted signal. When SNR values are larger than 0, the received signal operates beyond the noise floor. On the other hand, when its values are smaller than 0, the received signal operates under the noise floor. SNR is used as an evaluation metrics to define the sensitivity performance of radio communications. When the SNR values increase, it means that the received wireless signal is less corrupted. Therefore, a signal achieving a high *SNR* is a high-*quality* signal. Normally the noise floor is the physical limit of signal sensitivity, but one of the characteristics of LoRa is that LoRa can demodulate signals maximum -20 dB under the noise floor. This study evaluates the link quality of the LoRa using measurements based on these two wireless signal performance metrics.

In addition, the ratio of received packets to the number of transmitted packets also called the Received Packet Ratio (RPR), is calculated at each configuration setting. The RPR provides information about wireless communication reliability.

$$RPR = Received\ Packets\ \div Transmitted\ Packets \tag{4}$$

3.6 Summary

Chapter 3 describes methodologies. For data collection, LoRa module is configured with 36 PHY parameter settings – three spreading factors (7, 9, 11), three signal bandwidths (125kHz, 250kHz, 500kHz), and four coding rates (4/5, 4/6, 4/7, 4/8). Test devices are the Dragino LoRa shields equipped with SX1276 radio modules in 915MHz frequency bands. The experiment is conducted at three different distances – 10m, 20m, and 40m – between LoRa TX node and LoRa RX node in indoor office buildings in Purdue University West Lafayette Campus, US.

The RSSI and SNR are measured to characterize the link performance of Lora. The Received Signal Strength Indication (RSSI) and Signal-to-Noise Ratio (SNR) are two Physical level indicators available on wireless radio chips. In addition to them, the LoRa communication reliability is calculated based on the Received Packet Ratio (RPR) out of transmitted packets with different PHY settings at each distance.

CHAPTER 4. RESULT

This chapter explains experiment results and investigates how LoRa physical layer parameters affect its link performance. Section 4.1 explains how analytics with collected data is conducted. The following section describes the LoRa PHY parameter settings and displays a table that contains the information of the average RSSI and SNR values of each PHY settings in different distances of indoor experiments. Section 4.3 covers observed study results of both field experiments presenting result analysis and visualizations. Lastly, section 4.4 summarizes the testing results.

4.1 Data Analytics

This study experiments direct communication between LoRa TX and LoRa RX in a fixed distance using microcontroller units attached with LoRa shields without using LoRa gateway. LoRa TX end nodes are located 1 (±0.1) meter above the ground level. The experiments are conducted with two LoRa machines communicate at three different distances in indoor spaces: 10 (±0.5) meters, 21 (±1.0) meters, and 40 (±1.5) meters. Arduino LoRa library is used for LoRa radio signal communication between TX and RX.

In this study, LoRa direct communication is done using a single channel. Due to this reason, LoRa TX and RX must be configured in the same spreading factor, bandwidth, and coding rate. LoRa senders are configured in different spreading factors sending a packet in a packet size of 17(byte) each time at every three (+0.5) seconds. LoRa receiver is configured to change the spreading factor at each time after it receives a packet. The receiver board is connected to the laptop reading packet messages sent from the LoRa transmitter board through the Arduino serial port.

In order to stream and store live data, received packet data is read through the serial port from Arduino IDE into the spreadsheet with PLX-DAQ on Windows. PLX-DAQ is a parallax microcontroller data acquisition macro tool for Microsoft Excel. This tool provides simple spreadsheet integration for data analysis by collecting field data in real-time. Once data collection is completed, data analysis and visualization processes are practiced in Python Jupyter Notebook.

4.2 LoRa PHY Parameter Sets

As presented in table 4.1, the LoRa module is configured with 36 LoRa physical layer parameter settings - 3 spreading factors × 3 bandwidths × 4 coding rates. The LoRa receiver node receives two things during the packet reception - RSSI and SNR. The LoRa communication reliability is calculated based on the Received Packet Ratio (RPR) out of transmitted packets with different PHY settings at each distance.

Table 4.1. Results of Each Parameter Setting at Different Distances

PHY Parameters			10 meters			20 meters			40 meters		
SF	**BW***	**CR**	**RSSI**	**SNR**	**RPR**	**RSSI**	**SNR**	**RPR**	**RSSI**	**SNR**	**RPR**
7	500	0.8	-72.57	5.62	100	-62.78	5.76	98	-97.16	-2.21	77
7	500	0.7	-69.69	5.69	100	-62.27	5.79	98	-96.47	-1.62	76
7	500	0.6	-67.76	5.91	98	-62.63	6.01	99	-96.22	-1.19	77
7	500	0.5	-68.49	5.8	100	-63.05	5.93	100	-96.23	-1.51	78
7	250	0.8	-51.51	10.1	100	-73.82	9.74	100	-98.76	2.2	82
7	250	0.7	-51.26	10.12	100	-72.46	10.09	100	-98.63	1.41	87
7	250	0.6	-52.04	9.82	100	-75.62	9.84	100	-98.97	0.29	87
7	250	0.5	-52.17	9.75	99	-77.07	9.82	100	-99.73	-0.07	93
7	125	0.8	-59.21	9.75	100	-62.99	9.69	100	-98.88	4.21	100
7	125	0.7	-57.88	10	100	-59.62	9.73	100	-97.99	4.73	98
7	125	0.6	-58.09	9.75	100	-60.2	9.69	100	-97.76	4.78	100
7	125	0.5	-58.25	9.72	100	-60.14	9.71	100	-98.69	4.11	100
9	500	0.8	-55.21	7.87	100	-66.8	7.33	100	-99.23	-5.01	91
9	500	0.7	-53.53	7.88	100	-64.95	6.84	100	-96.51	-1.38	100
9	500	0.6	-53.12	7.76	100	-64.07	6.82	100	-95.68	-0.19	99
9	500	0.5	-52.54	7.84	100	-62.39	7.49	100	-95.44	-0.51	100
9	250	0.8	-59.99	13.27	100	-65.95	10.59	99	-100.52	0.23	99
9	250	0.7	-57.83	13.3	100	-64.65	10.62	99	-97.33	4.14	100
9	250	0.6	-56.85	13.25	100	-64.1	10.48	99	-98.27	3.34	100

Table 4.1 continued

9	250	0.5	-55.94	13.64	100	-63.11	11.45	100	-97.95	3.44	100
9	125	0.8	-58.65	13.32	100	-66.96	9.89	99	-99.41	5.03	88
9	125	0.7	-56.54	13.57	100	-65.42	10.25	100	-99.7	4.16	92
9	125	0.6	-56.2	13.38	100	-64.74	9.94	100	-99.91	3.77	100
9	125	0.5	-55.81	13.52	100	-64.25	9.91	100	-99.18	4.62	84
11	500	0.8	-58.52	7.08	100	-66.79	7.71	100	-99.23	-1.48	100
11	500	0.7	-57.25	6.18	100	-65.2	7.88	100	-99.49	-5.01	97
11	500	0.6	-56.76	7.78	100	-64.41	8	100	-98.52	-2.74	99
11	500	0.5	-56.69	8.32	100	-64.13	7.5	100	-98.19	-2.8	100
11	250	0.8	-55.06	9.76	100	-74.94	11	100	-100.25	2.77	99
11	250	0.7	-52.82	9.53	100	-74.38	11.26	100	-98.68	3.41	100

*in kHz

4.3 Experiment Results

At each parameter setting, 100 messages are transmitted from the LoRa TX node in the indoor space. The analytic dataset contains collected values of spreading factor, bandwidth, coding rate, packet size (fixed to 17 bytes), date, time, RSSI, and SNR. With combinations of 36 parameter settings, a total of 3,600 messages are analyzed in each field test. The ratio of received packets to the number of transmitted packets, the so-called Received Packet Ratio (RPR), is calculated at each configuration setting to evaluate the reliability. Three experiments were conducted in the indoor space at different communication distances: 10 meters, 20 meters, and 40 meters. The RSSI, the SNR, and the RPR are used as metrics to analyze the LoRa signal performance of different PHY parameter settings at each distance.

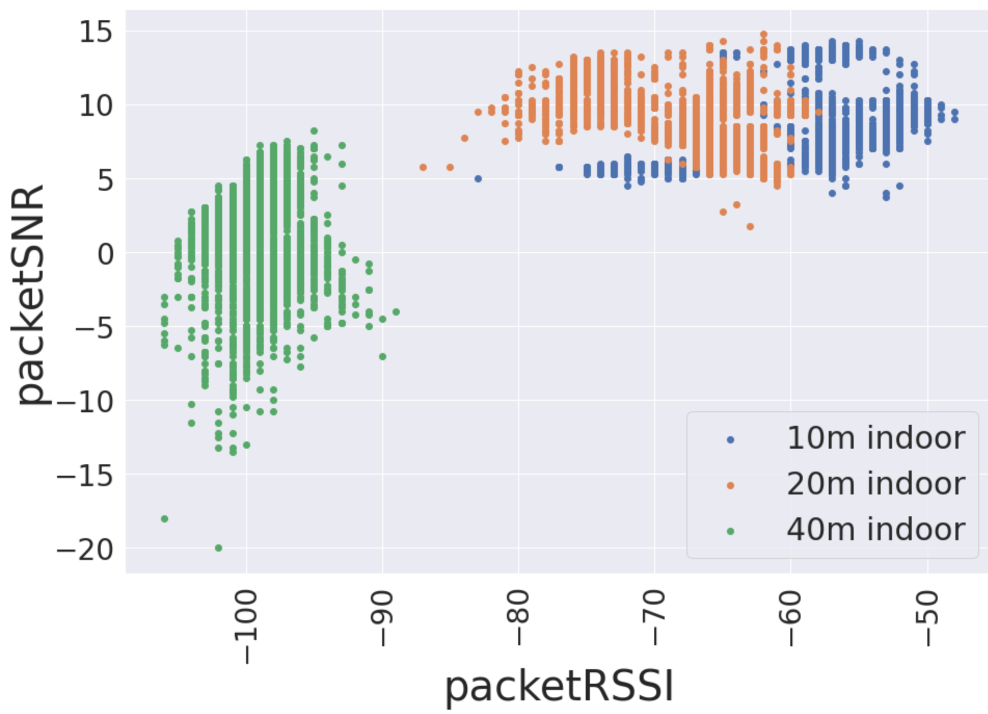

Figure 4.1. The RSSI and SNR in Indoor at Different Distances.

The LoRa signal performance is obviously affected by its communication distance. In figure 4.1, both the RSSI and the SNR do not show a huge difference when the signal distances were only at 10 meters and 20 meters away in indoor space. In the same environment, however, both metrics evaluated lower signal quality at a 40-meter distance as the distance got further. When the distances were at 10-meter and 20-meter, the SNR from all packets were measured above 0, but at the 40-meter communication range, almost half of the packets were received with the SNR values below 0. It means that the further the communication distance, the more packets delivered with negative SNR values.

Out of 3,600 transmitted packet messages, 3 were missing, and 3,597 samples were successfully received in a 10-meter indoor space. With 9 messages lost in a 20-meter distance indoor experiment, 3,591 data were received out of 3,600 transmitted data. During the sample data collection in a communication distance of 40 meters, the greatest number of 197 packets were not delivered properly. Accordingly, only 3,403 packets reached the RX node. Hence, the result section is explained with a total of 10,591 samples.

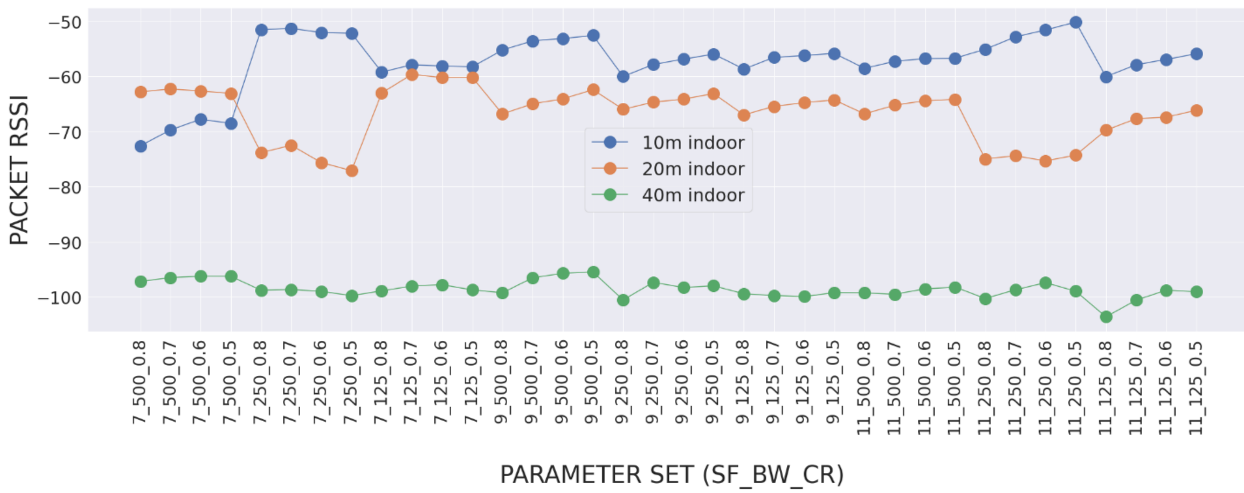

Figure 4.2. The Average Received Signal Strength Indicator (RSSI) by PHY Sets in Indoor at Different Distances

Figure 4.2 visualizes the average RSSI values of each PHY parameter sets at different distances. The variation of average RSSI values of parameter settings reduces as distance increases. For example, when the distance is 40 meters, the RSSI values of all the PHY settings were around -100 dBm. Therefore, it is hard to determine how the RSSI values relate to LoRa PHY layer parameters. Instead, the RSSI seems to be affected by communication distance.

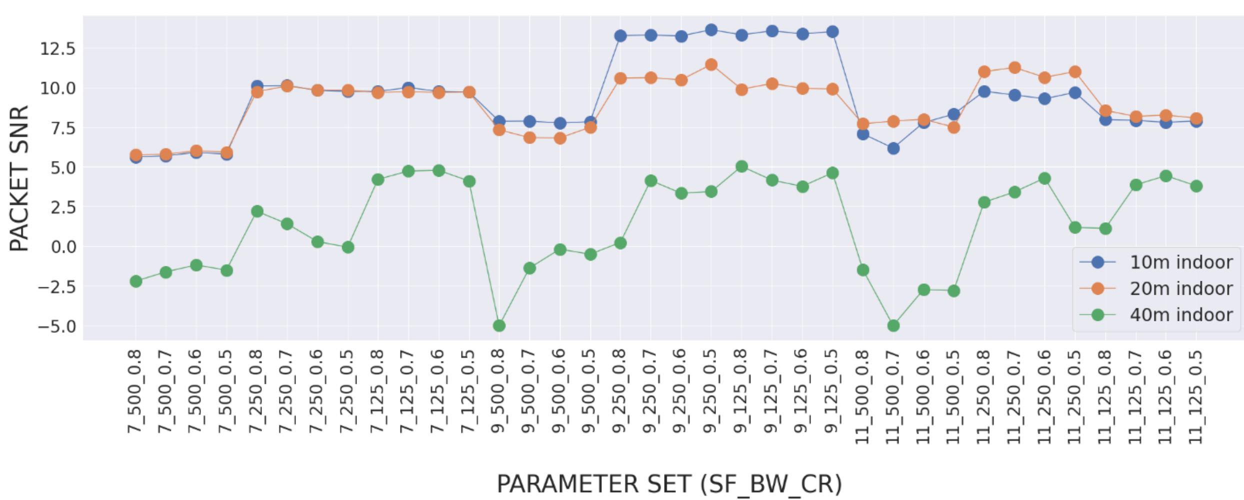

Figure 4.3. The Average Signal-to-Noise Ratio (SNR) by PHY Sets in Indoor at Different Distances

Unlike the RSSI, the experiment results in figure 4.3 show that the SNR values seem to get affected by signal bandwidth at all three distances. Among three LoRa signal bandwidths, PHY parameter settings with BW 500kHz produced the lowest SNR values. In order to investigate how the signal bandwidth impact the SNR, the following section provides the most commonly used statistical tests to establish a relation between each LoRa PHY parameter and performance metric value.

The Pearson's Correlation Coefficient with P-value is presented to analyze how PHY parameters relate to LoRa performance using the collected data samples from the field experiments. The Pearson's Correlation Coefficient is used to statistically measure the strength of a linear association between the two variables. Equation (5) is the formula of the Pearson's Correlation Coefficient.

$$r = \Sigma(x_i - \bar{x})(y_i - \bar{y}) \div \sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2} \tag{5}$$

r = Pearson's Correlation Coefficient

x_i = values of the x-variable in a sample

x = mean of the values of the x-variable

y_i = values of the y-variable in a sample

y = mean of the values of the y-variable

4.4 Statistical Significance Test

To draw a conclusion whether the observed sample is expected to be true in the population, the researcher provides the result of conducted statistical significance tests in this section. The statistical significance test provides mathematical evidence to describe the relationship between the PHY parameters and the link performance metrics (the RSSI, the SNR, and the RPR). Specified null and alternative hypotheses are below:

- H_o: there is no significant linear correlation between *PHY parameter and *link performance.
- H_a: there is a significant linear correlation between *PHY parameter and *link performance.

*PHY parameter = {SF, CR, BW}, *link performance = {the RSSI, the SNR, the RPR}

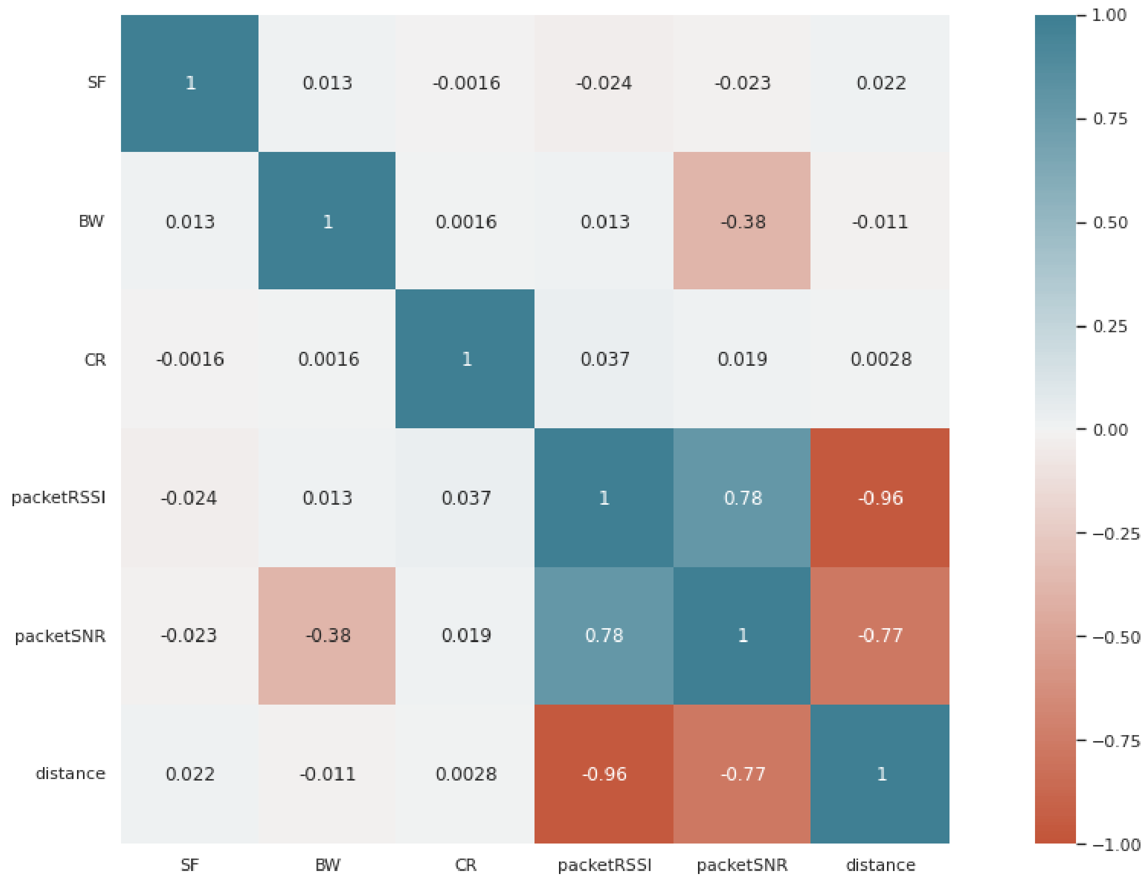

Figure 4.4. LoRa Parameter and Signal Performance Correlation Heat Map in Indoor Environment at Different Distances

The above heat map presents the calculated Pearson's Correlation Coefficient between LoRa PHY parameters, and two metrics measured for LoRa performance evaluation. According to the output displayed in figure 4.5, the spreading factor barely has a negative correlation with both the RSSI and the SNR. Typically, it is known that a higher spreading factor allows better receiver sensitivity. From the experimental samples, spreading factors did not significantly relate to either the RSSI or the SNR. In figure 4.4, however, low performance in reliability was observed when the LoRa module is configured with spreading factor 7 in most cases and with spreading factor 9 in a few cases in a 40-meter communication distance.

It is also observable that the signal bandwidth relates to both the RSSI and the SNR. Its correlation coefficient to the signal-to-noise ratio (SNR) seems to be quite linearly relative with a negative value of -0.38 and some relation with a calculated correlation coefficient of 0.013 to the

RSSI. The coding rate indicates a minimal correlation coefficient to both the RSSI and the SNR, with positive values of 0.04 to the RSSI and 0.02 to the SNR. Thus, according to the correlation coefficient test, only signal bandwidth out of three PHY parameters seems to have some relationship to LoRa performance. However, to decide if the interpretation of the variables' relationship is statistically significant, table 4.2 provides how PHY parameters and the link performance metrics (the RSSI, the SNR, and the RPR) are related, providing correlation coefficients and p-value at the significance level to 0.01 ($\alpha = 0.01$).

It is obvious that any radio signals achieve decreased link performance over longer distances. In this study, the researcher focuses on finding the answers to the research question represented in section 1.3, which is "How do different configuration settings of LoRa physical layer parameters - spreading factor, bandwidth, and coding rate - affect the quality of LoRa performance, operating on 915MHz ISM band in indoor office environments."

Table 4.2. Correlation Coefficient with P-value of LoRa Parameters and Performance in Indoor

Variable 1	Variable 2	Correlation Coefficient	P-value
Spreading Factor	RSSI	-0.02	0.0145
Spreading Factor	SNR	-0.02	0.0196
Spreading Factor	RPR	0.32	0.0007
Bandwidth	RSSI	0.01	0.1675
Bandwidth	SNR	-0.38	0.0000
Bandwidth	RPR	-0.17	0.0876
Coding Rate	RSSI	0.04	0.0001
Coding Rate	SNR	0.02	0.0448
Coding Rate	RPR	-0.06	0.5343
Distance	RSSI	-0.96	0.0000
Distance	SNR	-0.77	0.0000

According to table 4.2, among PHY parameters, signal bandwidth has some negative correlation to the SNR with the P-value is smaller than the significance level ($\alpha = 0.01$). Therefore, it concludes that there is a significant correlation between signal bandwidth and the signal-to-noise ratio.

4.6 PHY Parameters and Performance Metrics

Besides distances, among physical layer parameters, the signal bandwidth impacts the most on the SNR negatively based on the statistical evaluation in the previous section. As expected, the higher the bandwidth, the higher the data transmission rate, but the lower the sensitivity to noise.

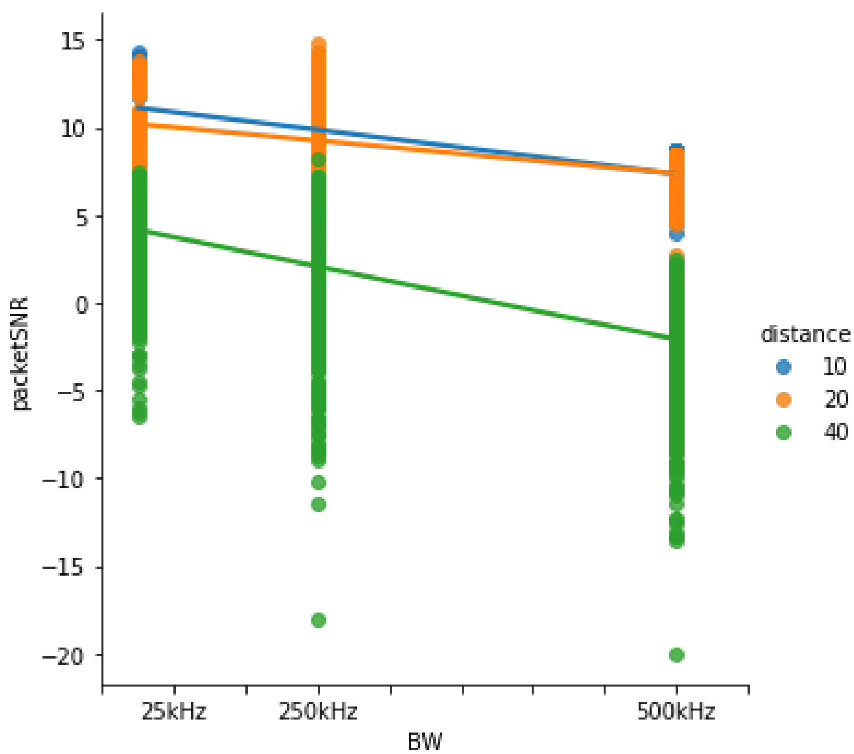

Figure 4. 5. Negative Linear Correlation between Signal Bandwidth and the Signal-to-Noise Ratio (SNR)

In figure 4.6, the Received Packet Ratio at each PHY parameter setting in different distances is displayed. By analyzing the RPR, it is clearly observed in figure 4.7 that the spreading factor affects LoRa performance, specifically LoRa reliability. In most cases, settings with a higher spreading factor showed higher reliability at further distances. In other words, the spreading factor influences the readings.

Unlike other physical layer parameters, the experiment results show that the coding rate does not significantly correlate with any of the LoRa performance metrics. However, in figure 4.8, the coding rate shows some minor relation with the LoRa reliability as the distance increases. Therefore, it can be explained that the coding rate influences the performance as distance increases. It will require additional testing in the future with increased testing distances to prove whether LoRa reliability decreases with a higher coding rate.

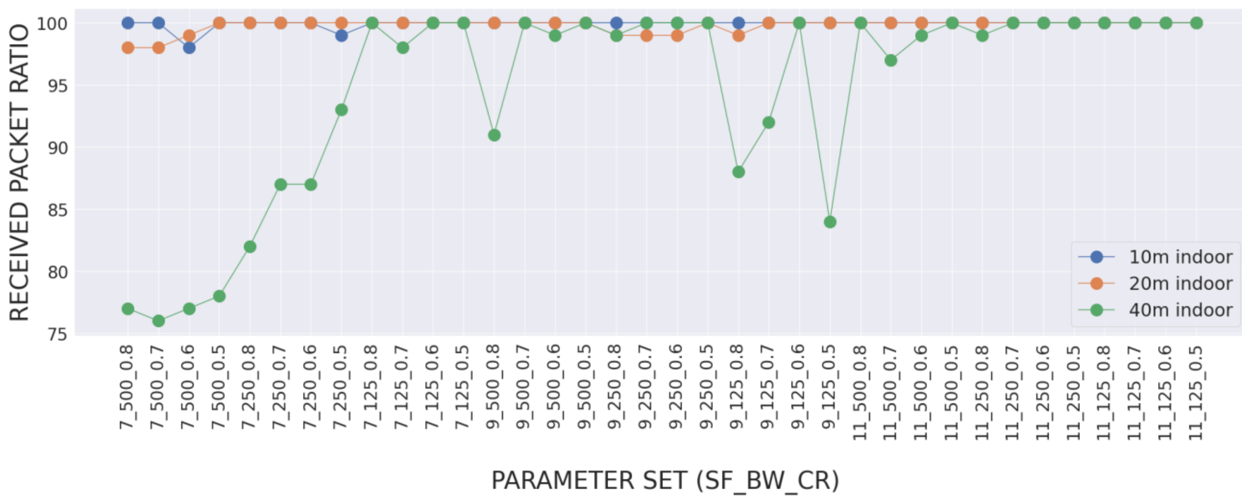

Figure 4.6. The Received Packet Ratio (RPR) by PHY Sets in Indoor at Different Distances

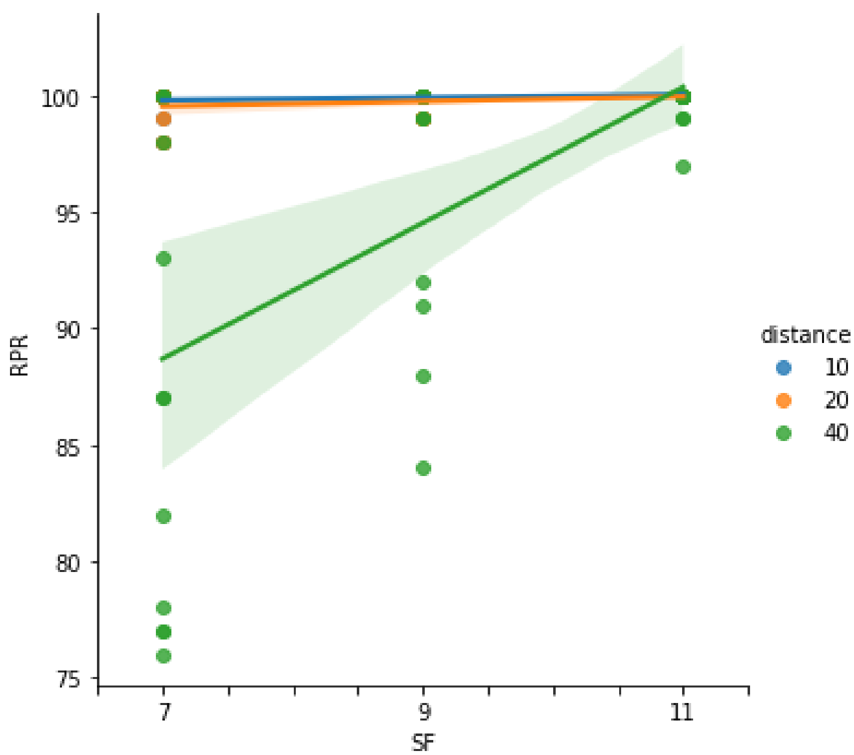

Figure 4.7. Positive Linear Relation between Spreading Factor and the Received Packet Rate

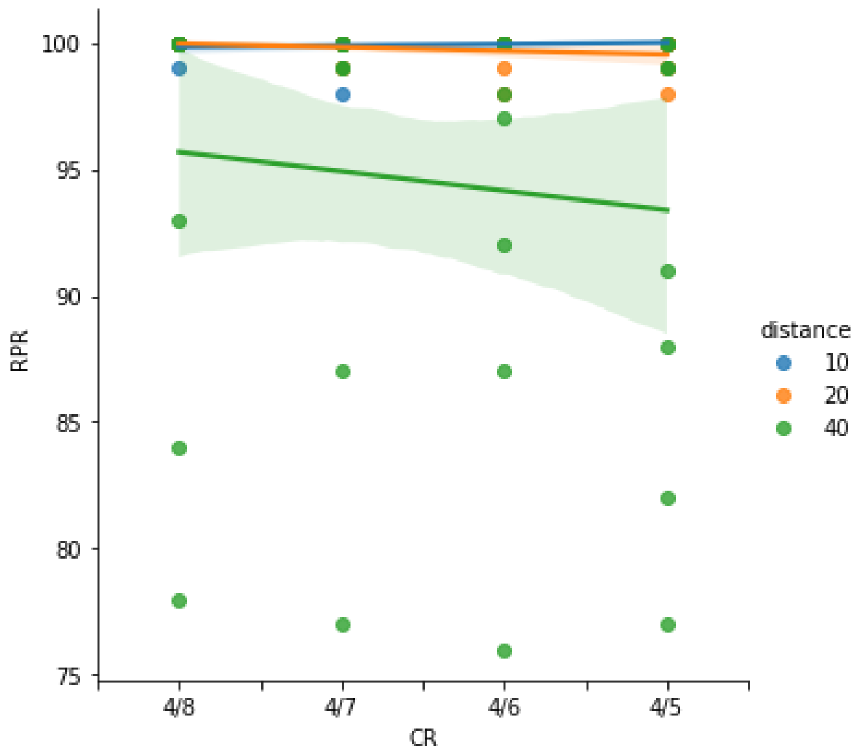

Figure 4.8. Linear Relation between Coding Rate and Received Packet Ratio by Distances

CHAPTER 5. CONCLUSION

Chapter 5 consists of two parts. Section 5.1 concludes this study and explains the experimental results. The last section provides the researcher's ideas for future works upon this study.

5.1 Conclusion

The purpose of this research was better to understand LoRa signal performance with its possible parameter configurations. Many other parameters can be considered when testing wireless signal performances, such as transmission power, distances, payload, number of channels, frequencies, and more. This thesis focused on studying how LoRa physical layer parameters (spreading factors, signal bandwidths, and coding rates) impact LoRa radio performances in different set distance ranges in indoor spaces in the campus area. For data collection purposes, 100 packet messages were transmitted at each parameter setting at distances in 10m, 20m, and 40m. In all cases, 10,800 packets were transmitted from LoRa TX node to LoRa RX node, and 10,593 packets were successfully received. In chapter 4, the researcher presented experimental results and statistical analysis to explain better the relationships between LoRa PHY parameters and its link performance in indoor office space using an SX1276 radio module operating in the 915MHz at different distances. Upon the completion of the experiment, the researcher utilized three link performance metrics: the Received Signal Strength Indicator (RSSI), the Signal-to-Noise Ratio (SNR), and the Received Packet Ratio (RPR). The RSSI determines how strong the received packet signal is, the SNR evaluates signal sensitivity to noise, and the RPR quantifies LoRa link reliability. Then, the researcher analyzed the relationship between LoRa physical layer parameters to the performance metrics. It was hard to determine how the RSSI relates to any of the LoRa PHY layer parameters. Instead, the RSSI markedly varied by communication distance.

From the results of statistical significance tests, this study concludes that there are two significant correlations between PHY parameters and link performance metrics. Firstly, with the P-value smaller than the significance level ($\alpha = 0.01$), there is a significant correlation between signal bandwidth and the signal-to-noise ratio. Therefore, its null hypothesis – Ho: there is no significant linear correlation between signal bandwidth and signal-to-noise ratio – can be rejected.

Lastly, to investigate the relation of the spreading factor to LoRa performance, the testing result from collected samples shows that with the P-value smaller than the significance level ($\alpha = 0.01$), there is a significant correlation between the spreading factor and the received packet ratio. However, this study could not provide enough evidence to reject the other null hypotheses from the collected sample.

5.2 Future Works

In addition to signal quality evaluation, LoRa signal performance can be evaluated based on ToA (Time-on-Air) and energy efficiency to study LoRa technology from various perspectives.

Other than the physical layer parameters, different parameter options can be considered to investigate how they influence LoRa wireless communication performance. For instance, transmission power (TP), career frequencies, payload sizes, and more on the LoRa signal performance. TP is a modulation parameter that can be configured from 2dB to 20dB. According to Semtech, the higher the transmission power, the higher power consumption and SNR (Semtech, 2019).

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