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Real Time Performance Testing of LoRa-LPWAN Based Environmental Monitoring UAV System

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By

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ABSTRACT

Aerial drones are emerging in industrial and environmental monitoring as they are effective tools that are able to reach far and isolated areas. However, the regularity communication developments have not grown as fast as the technology needs. Either due to the lack of communication coverage or power inefficiency. As a result, some other solution should be proposed such as the internet of things. Internet of Things technology has a great potential of becoming a leading industry since it makes objects able to communicate with each other. IOT/M2M (Internet of Things/Machine-to-machine) communication could be used in a wide range of applications such as environmental surveillance and monitoring systems. These systems could be fixed ends or moving end like an Unmanned Ariel vehicle (UAV). In this case, LoRa/LPWAN (Long Range Communication) / (Low Power Wide Area Network) is selected to be the best candidate, since it provides a wide coverage area and power efficient systems. This thesis develops and tests a communication scheme prototype for environmental UAV monitoring system using LoRa-LPWAN. Also, a functional testbed for testing the prototype is proposed as well. The prototype was tested in different environmental sites such as line-of-sight and non-line-of-sight environments. The developed scheme performs successfully in harsh environments and its readings were fully documented throughout this thesis.

DEDICATION

"If my mind can conceive it and my heart can believe it, then I can achieve it "

Muhammad Ali

To

My father Adil

For earning an honest living for us. And for supporting and encouraging me to believe in my self

My mother Bushra

For spreading love and tranquility and for being the first teacher in my life

My wife Ola

For being the first supporter. A strong soul who taught me to believe in hard work and that so much could be done with little

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LIST OF ABBREVIATIONS

UAV – Unmanned aerial vehicles

IOT- Internet of Things

M2M- Machine-to-machine

LoRa- Long Range Communication

LPWAN- Low Power Wide Area Network

M2M – Machine to Machine Communication

dBm - decibel-milliwatts

PV - Photovoltaic

GUI-graphical user interface

MCU- Microcontroller Unit

QoS- Quality of Service

PER- Packet Error Rate

RSSI- Received Signal Strength Indicator

SNR- Signal to Noise Ratio

BW-Bandwidth

Khz-Kilohertz

SF-Spreading Factor

PDR-Packet Delivery Rate

PLR- Packet Loss Rate

CRC-Cyclic Redundancy Check

TX-Transmitter

RX-Receiver

PHY- Physical Layer Factors

CR - Coding Ratio

LOS – Line-of-Sight

ISM (Industrial, scientific and medical)

BER Bit Error Rate

GPS-Global Positioning System

CSS-Chrip Spread Spectrum

QoS- Quality of Service

ISM- Industrial, scientific and medical

BER Bit Error Rate

Bps – Bit per second

MQTT (Message Queuing Telemetry Transport)

1. INTRODUCTION

1.1 Introduction

Environmental issues have become an extremely huge concern in last few decades. Which could be considered as a harmfully affecting the living organisms as well as certain objects. The environmental changes could be caused by pollution in all its kinds, air pollution, water pollution and climate changes.

Air pollution is the most serious kind between these environmental threats. Since it is an urgent problem that has to be ceased and eliminated. In modern times, and due to the extreme advancement in industrial and transport areas along with the thermal and nuclear power generation plants and that causes a serious threat to human life as well as all living surroundings. Air pollution could also be caused by wildfires which has a huge impact on air pollution. And recently, wildfires took all the attention in all fields.

Wildfires are a large uncontrolled blaze which quickly spread out through natural and rural areas; they are fed by wind and dry lands. Land fires could be caused by humans or natural increases in temperature. In that, there are three main components that need to be addressed to cause wildfires: fuel, oxygen, and heat. However, many wildfires caused by a natural increase in temperature provide the accurate climate to initiate a blaze. On the other hand, about 90% of wildfires are caused by human activities such as campfires or lit cigarettes. It has been obvious that wildfires have been a devastating damage to people's properties and lives. The average damage a wildfire causes each year in the western United States is up to 5 million acres of burnt land. Wildfires leave nothing but damage, burnt paths, and huge environmental issues [1]. In Canada, the wildfires near William Lake British Columbia had an estimated damage cost of around $100 million of summer 2017. It caused around $100 million in damages to people's properties, for example, their homes, vehicles, and businesses according to reports by insurance companies. Another $27 million in damages was caused by Elephant Hill wildfires in B.C. in 2017 and an evacuation of tens of thousands of B.C residents was launched [2]. However, the costliest wildfires in Canadian history is that of Fort McMurtry in 2016; according to reports by MacEwan University, the total cost of the wildfires exceeded $8.86 billion. The flames forced around 90,000 inhabitants to flee their properties and move out of the city which resulted in severe damage to the economy [3].

Due to these tremendous devastations, there have been numerous attempts to look for solutions. These solutions could be technical and technological approaches that save lives, and also where damages could be eliminated. A continuous early measuring the concentration of gases like CO and CO2 could be one solution where gas sensors could be used to detect the required measurements. In this particular case, a small aircraft without a human pilot abroad could be the best option since these Unmanned Aerial Vehicles (UAVs) are low cost; they are able to fly for hours until they need to be recharged again. For communication aspects, long-range and low-power communication could be used for this particular case, because technology such as WiFi is a high power consumption and poor coverage range. Also, a cellular network would not be a suitable option due to its lack of coverage. As a result, Internet of Things/Low Power Wide Area Network (IOT/LPWAN) has emerged to fulfill the communications for such an application. The long-range and low-power technology which is referred to as LoRa [4] is a perfect candidate for applications like smart sensing technology, health monitoring, smart metering, and environment monitoring sensing [5]. In general, this application could be also used in any kind of gas detection and air pollution; by attaching analoge or digital sensors it is using the same approach. The OECD (Organization for Economic and Development) [6] shows that the estimation of the economic cost of air pollution is about $1.72T resulting in serious medical conditions. Therefore, this kind of application could be used to reduce air pollution since it is not a practical way to measure air quality across a widespread area [7]. Furthermore, a literature survey reveals LoRa is a successful implementation for a radiation leak detection deployment by using sensors and gateways embedded with LoRa technology, and low power protocol. For this purpose, radiation levels of nuclear power plants can be measured and leakage detections are performed to ensure the safety of the employers and inhabited areas [8].

1.2 Problem Statement

Merging the IOT/M2M technology with the environmental measurements instruments that minimizes the power consumption and provide a reliable communication scheme is a better solution for a continuous air quality measurements using UAV technology systems.

Envirodrone [9] is an environmental health service in Windsor Ontario, which offers a complete unmanned aerial vehicle data service using a state of the art drone technology and remote sensing software. The company is aimed to design an air-quality multifunctional UAV monitoring system that can be used to sense the concentration of gases in the air such as, Carbon dioxide (CO_2), Nitrogen dioxide (NO_2), Carbon monoxide (CO), and etcetera. This thesis focuses on the design, implementation and the test of a reliable low-cost prototype for a communication scheme that could be used to connect the UAV with grounded sensors. And this platform could be used in many applications as mentioned earlier.

1.3 Thesis Objectives

The main objective of this thesis is to develop a low-cost and low power consumption long-range communication for the required design. In order to initiate this concept, an up to date IOT/M2M LoRa communication technology should be examined to understand the pros and cons of this project. For this purpose, a software testbed is created as a part of this thesis objective. The testbed is capable of testing the performance of LoRa; examining the limitations and capabilities of this powerful communication technology.

1.4 Background

The Internet of Things (IOT) refers to the network of connected physical objects. These objects could be devices, vehicles, home appliances, and other embedded electronics and sensors. IOT makes these objects able to exchange data, and it provides a reliable connectivity with minimum power consumption and a low-cost but a higher-efficiency, resulting in huge economic improvement [10]. According to [11], by 2020, the IOT industry will significantly rise and will be about $8.9 trillion, after it jumped from $2.99 trillion in 2014. The study also shows that there will be about 31 billion connected devices by the year 2020. This number will reach around 75 billion devices by the year 2025. The figure below shows the IOT connected devices installed worldwide in billions.

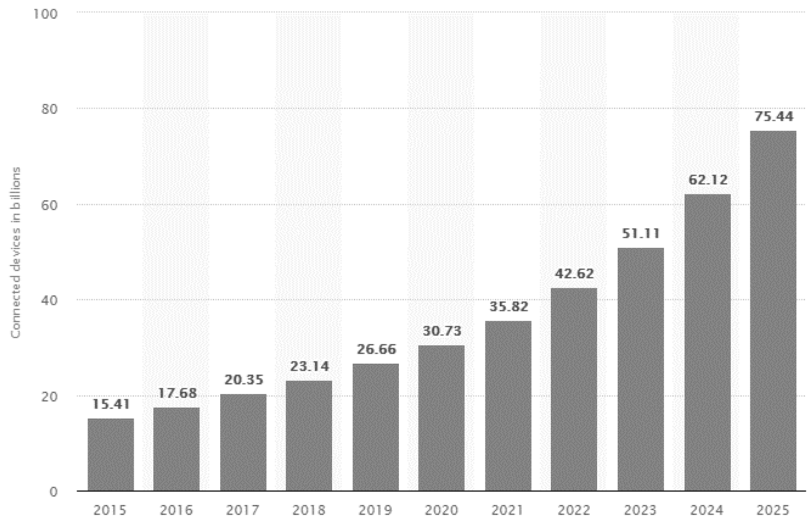

Figure 1 IOT Connected Devices for ten years [12]

From the statistics above, it is clear that IOT will have a tremendous worldwide increase in the next decade due to its outstanding performance and magnificent success. The world is going smarter and our goal is to use the benefits as much as possible to bring us one step closer to any required power-efficient high-performance design. Using IOT reduces the interaction between humans and machines and provides a direct connection between machines. This allows machines to communicate with each other without human intervention, which is also known as M2M Communication [13]. IOT could be implemented by short-range transmission technologies such a ZigBee [14], however, this kind of technology will not fit where long-range communication is a must since it requires a large coverage area.

1.5 Thesis Organization

The remaining parts of this thesis are organized as follows: Chapter two discusses the related work in investigating LoRa. This chapter addresses all the citation and related papers that is relevant to the thesis work. Chapter three reveals the main parts of system design and implementation. It also shows the system model and metholog, all the design parts are discussed in details and illustrated in figures. Chapter four discusses the experimental testing results, and measurements. All measurements are illustrated in diagrams and tables. Finally, chapter five shows the conclusion and the suggested future works.

2. RELATED WORK

2.1 Introduction

It is very important to understand and discuss the related works of this thesis which have been prepared in advance, and the main references used for citations. In this chapter, the main related papers are discussed and divided into subsections. Section 2.1 focuses on the main related design. Section 2.2 discusses the creation of testbed for different LoRa applications. Section 2.3 focuses on the investigation of LoRa/LPWAN performance and coverage for both indoor and outdoor applications. However, section 2.4 discusses the summary of all related works.

2.2 The General Design

Starting with the main design concept, Liu et al. in [15] show a similar design with two fixed motes which differentiates itself from my proposed thesis. The recommended system is a sensor network based on LoRa Wireless Communication technology using a number of air pollution sensors like (NO_2, SO_2, O_3, CO, PM_1, PM_{10}, and $PM_{2.5}$) and a solar PV-battery as a power source and the design is connected to graphical user interface (GUI). The proposed design is an IOT-based real-time air quality monitoring for gas concentration measurement. The sender side of this design consists of gas concentration sensors connected to a Microcontroller Unit (MCU). While the other side which is the receiver (Rx) side is a simple LoRa mote properly fed to a computer. The range test was conducted with about 20 dBm transmitted power and gas concentration measurements were successfully taken. This work concludes that LoRa technology is an outstanding long-range scheme for such a design.

Petric et al [16] proposed a real-world implementation of LPWAN using LoRa FABIAN including examining the quality of service (QoS) that the network can provide under specific conditions along with the performance metrics like packet error rate (PER). Physical-layer related metrics, such as the received signal strength indicator (RSSI) and signal to noise ratio (SNR) are also concluded in this paper. For testing scenarios, some specific parameters were fixed, for instance, the bandwidth (BW) was 125 KHz, the coding ratio was fixed to be 4/5, and the packet payload 25 bytes. However, other parameters such as spreading factor (SF), antenna length, surroundings, and distance were varied and the test took place in both suburban area and city center crowded areas of Rennes city northwest of France. This paper concludes that Lora technology is an excellent outdoor choice either in urban or in rural areas, however, the antenna has a major effect on the performance of this technology. RSSI could not be the best metric to rely on since measurements do not exhibit a strong correlation. In that SNR could be a better metric according to the measurements. The reported range test measurements in this work show a significant success for both city and rural areas.

Lee et al [17] show a complete design and implementation of large-area IOT sensors using LoRa mesh wireless networking with better packet delivery rate (PDR) over 600 meters x 800 meters urban area. The sensors are distributed in a large area, and LoRa mesh network helps to collect, accumulate, and send data over the area. The (PDR) was tested for different distances. For instance, with SF=6, (PDR) was around 40% for 400 meters distance and was dropped after 500 meters. Doubling the (SF) increases the coverage and the (PDR) dramatically, with 98% for 500 meters. Therefore, the higher the SF the more coverage and better PDR.

On the other hand, Wixted et al [18] designed low-cost remote sensing applications where the performance was evaluated across the central business district of Glasgow city, Scotland. Three test runs were conducted: First, LoRa wireless test which investigates the RSSI of the technology. Second, LoRaWAN testing, and the third test was the reliability. This work displays encouraging outcomes when using multiple gateways, also the network coverage reached into places that were considered problematic. Variation of RSSI appears more consistent in tree farms rather than in open areas/rural areas.

Wang et al [19] also focus on designing a PM2.5 air quality pollution sensors equipped with a LoRa module to transmit its PM2.5 measurements to the server which is also a LoRa transceiver. In addition, the authors focused on how the Packet Loss Rate (PLR) affected by the distance between end-devices and the gateway. This shows the relationship between factors like the transmitted power, payload length and the antenna angle and the performance of LoRa. It determines how 915 MHz LoRa performs in an open area when packet size changes along with the distance between Tx and Rx on the campus of National Chiao Tung University, Taiwan.

A comprehensive LoRa performance evaluation measurement shows that the PLR varied between (60-90%) thus, this high percentage is due to the indoor communication where the end devices were placed inside a building. That leads to prove that LoRa could not be the best option for indoor IOT applications. However, the readings show that there was no consistent relationship between the payload and PLR. For outdoor testing, LoRa transceivers were configured with three different transmitted power 20, 11 and 2 dBm.

Real-time measurements show that there was no actual effect on the PLR for short distance transmission when Tx power varies. However, for long distance transmission (1 Km and more), Tx power may increase the packet reception ratio in some cases as shown in Table 1.

Transmission Power (dBm)	PLR (%)
20	0
11	23
2	68

Table 1 PLR VS Power for 1 Km Transmission [19]

2.3 The Creation of the Testbed

In this part, paper [20] and a part of [21] are going to be discussed. These two papers are related to how to create a testbed and simulation method for LoRa testing and take measurements which could be very helpful to this thesis. Haxhibeqiri et al in [20] proposed an algorithm of determining packets collisions and packet received with wrong cyclic redundancy check (CRC) which are referred to as bad packets. The algorithm specifies the number of the transmitter motes (Tx) and the number of packets transmitted by each mote along with SF, preamble length, header length and more. The percentage of packet loss due to collisions and the percentage of the wrong CRC received packets were measured. The total of both percentage measurements is considered to be the percentage of the total packet loss.

Haxhibeqiri et al [21] prepared a simulation method to test the scalability of LoRa a specific environment. The simulator was a Python script [22] that calculates the collisions based on a timing overlap between the transmission starting time, transmission time interval and RSSI values. In this simulator, three channels with 868 MHz are used while the SF varied and the coding rate was set to be 4/8. This is considered to be robust according to the article. Three vectors were generated: the SF vector, the RSSI vector and channel vector, all with length N, where N is the number of transmitters. For each transmitter, a channel is assigned randomly while SF and RSSI values are assigned separately. Two-dimensional array Nxn are generated, where N is the number of transmitters and n is the number of packets transmitted by each transmitter, in that the packet with very low RSSI is counted as lost. Total PLR percentage for a known given number of end nodes served by a gateway is calculated which equals to the sum of the lost packets and the number of packets received with the wrong CRC.

2.4 Investigation of LoRa/LPWAN Performance

LoRa technology is considered to be the ideal solution of any long-range low power communication design as discussed earlier. Therefore, LoRa should be tested in different environmental conditions depending on the design itself. This is used to check how it responds to extreme environmental changes as well as the parameters. Since the main focus of this thesis is on how well LoRa can perform in airborne monitoring systems, this section illustrates the performance of LoRa in different environments and areas for both indoor and outdoor coverage. There is a variety of locations where LoRa could be tested, such as on water surfaces like a river or sea. These are considered as complex environments where water, wind, sailboats and other obstacles are in [23] or, it could also be a land or some form of a farm as in indicated papers [24,25]. It also could be in urban areas where large buildings and obstacles exist along with a high range of interference and noise. Rural areas are also required since the proposed design also investigates the performance of LoRa in rural areas.

Li et al [23] discuss the application of LoRa LPWAN technology and its transmission performance in a sailing system. The authors applied the LoRa technology to a sailing monitoring system and the testing took place on a lake in Shanghai, China. Firstly, the coverage was investigated and analyzed when the base station was fixed near the center of the lake, in sequence a 4-meter high antenna was attached with no blocking, while the transmitter was deployed on a moving boat with a proper antenna. Excellent coverage range was recorded, where about 3000 meters with PLR less than 10% for SF 7 was analyzed and about 5000 meters for SF 11 was also examined. Secondly, PLR was tested in two different cases. The first case, both the transmitter and the receiver were deployed on moving boats. The antennas were one meter and four meters high for the sender and the gateways respectively. The measurement shows that there was only about 0.34 % of PLR with an average speed of 20 km/h and 400-meter distance between the motes. For the second case, the gateway was fixed on top of a 20-meter high building and was about 1 kilometer away from the lake, while the sender side is located on the moving boats in the lake. The PLR, in this case, shows acceptable results which were around 5-20% in some cases. In other cases, it was too high (around 60 %) due to major obstacles represented by high buildings between the sender and receiver. This paper, however, concludes that LoRa performs well in mobile systems which support the proposed design where mobility is a major concern for UAV monitoring systems.

In [24], Yim et al provide real-time measurements for LoRa performance evaluation in a tree farm in Indiana, United States, for agriculture investments discussing all physical layer factors (PHY) that have a clear impact on LoRa successes. The farm was a flat meadow, with small ridges in the middle. A vareity of trees are planted in 8-foot separate rows on the farm. For a 100-meter distance between the transmitter and the receiver, the PHY factors were specified periodically and the readings show that more than 66 % of the total packets were delivered successfully for 125 KHz bandwidth, SF=7 and Coding Ratio (CR=5). The study confirms that the higher SF the better coverage range and better PDR in most cases, and this applies to a larger distance as well. The bandwidth had the lowest impact on LoRa performance, however, it has a bigger effect on RSSI as concluded from the recorded measurements. Therefore, to secure high reliability in such an environment, maintaining higher SF and CR are crucial.

Continuing with the examination of LoRa in open spaces, Oliveira et al [25] presents a study that evaluates the range, signal quality and data delivery of LoRa in three cities in Portugal. Three potential scenarios are examined, one being rural and two are urban, where the authors stated that these environments are suitable to examine how the technology performs when direct Line-of-sight (LOS) is not guaranteed. For this purpose, one hundred, packets 75 bytes size each were transmitted in each trial and the transmitted power was set to the maximum (14 dBm). These specific values are considered to be reasonable to get proper values for RSSI, SNR, and PLR, according to [25]. The practical work shows that the coverage area was about 5.5 kilometer with SF=12 by fixing the CR and BW to 4/5 and 125 KHz respectively. Most of the packets were successfully delivered in the rural area and the delivery rate was high which reveals fewer obstacles between the Tx and Rx.

For the urban areas scenario, the authors selected two different cities, the first city contained an uneven plain with hills, while the second city was a flat town with small buildings. For both cities, the test is considered to be Non-Line-of-Sight (NLOS). The maximum coverage ranges achieved were decreased dramatically compared to the ones in the first testing scenario. Also, the communication service was inadequate which supports the idea that LoRa has limited capabilities in urban areas. Comparing the two urban scenarios, it can be concluded that the nature of the region affects the performance significantly.

On the other hand, it is also necessary to examine LoRa capabilities in indoor environments. The best location to do that is in an industrial environment where extreme ranges of noise and interference are produced by machines and communication modules. LoRa coverage and performance were tested in a machine shop in (place) [21] where a large number of trolleys are needed to communicate with a server during their movement across an auction area. In this paper, the author shows that LoRa was able to cover 3400 m2 with SF = 7. With SF=12, the total covered area was even higher. The experiments were done in Naaldwijk Netherlands, in a large industrial auction (250000 m2 covered area and several other open areas). The auction floor was a combination of an auction hall, storing zone, buffering zone, and a distribution area. The RSSI values were collected and recorded. The minimum value was on the ground floor and it was 23 dBm higher than the threshold. That is due to the NLOS communication caused by the objects between the motes. The average SNR values varied from 9.5 to 10 dB and were similar at different locations where the good reception was found. For PLR, some packets were received with wrong payload CRC and the range was (0.5 - 0.8%). The authors concluded that they were able to cover a large indoor industrial area with all SFs with almost no packet loss.

[26] Is a continuous work of [24], where the testing was extended to an open area at Stadium Mall, Purdue University, and West Lafayette, IN, United States. The authors made a comparison between the two works that reveals how LoRa performs in an open area with obstacles comparing the measurements in the tree farm. The authors divided the work into two settings, where each setting has a specific PHY value keeping the TX power fixed to 13 dBm (default). A 9-byte payload character type packet structure and 150 data packets were transmitted in each trial for distances 100,150 and 200 meters. The authors stated that the variation of the tree farm is bigger than the variation of an open area since PDR is much more sensitive to PHY factors.

2.5 Summary

The above chapter summarizes the main concepts of the related works that could be used to throughout this thesis study. An understanding of the system components needed in these papers and the current progress that has been achieved. However, these studies show that an appropriate technology must be selected carefully in order to design a long range communication scheme. Testing the system after designing it is a very important aspect according to the related papers. Most of the papers revealed the measurement using graphs and tables. Therefore, performance characteristics for LoRa/LPWAN are examined in the following chapters.

3. SYSTEM MODEL AND DESIGN

3.1 Introduction

LoRa is the most updated technology which is a part of LPWAN, it is presented by Semtech [27] and was specially designed for long-range low power communication. Using LoRa in long-range communication designs provides a low data transfer but a wide coverage area compared to its opponents. It also considered as a perfect solution to fit in battery-operated IOT applications along with special features such as the low cost and high capacity. LoRa also supports geolocation that enables GPS (Global Positioning System) tracking applications. Furthermore, LoRa is standardized that improves the exchange of information speeds and roll out of IOT applications. Also, it is well secured since it is embedded with end-to-end AES128 encryption [28]. LoRa is a physical layer technology which is a part of Chrip Spread Spectrum (CSS) that provides a more sensitive continuous phase between symbols in the preamble part of LoRa packet [29]. The following table shows the difference between the main LPWAN technologies:

	SIGFOX	**INGENU**	**LORA**
Estimate Coverage(Km)	Rural: 30-50 Urban: 3-10	15	Rural : 10-15 Urban : 3-5
Data Rate (Kb/s)	0.1	0.01-8	0.3-37.5
Nodes per gateway	10^6	10^4	10^4

Table 2 LPWAN Technologies Comparison [29]

3.2 The Physical Layer Factors of LoRa-LPWAN

3.2.1 PHY

PHY represents the physical layer parameters that could be configured to specific values in order to maintain the range, speed and the quality of service (QoS). These values are

a- Spreading Factor SF

Spreading factor is the number of symbols sent per bit of information. Where every bit of information in the payload is represented by multiple chips of information and the rate of spread of information is the (Symbol Rate).

For example: if the SF = 7 that means it has 2^{SF} chips per symbols.

Spreading factor is a very important PHY factor since it directly affects the communication abilities within the range of SF is 7 to 12. The higher spreading factor the wider coverage range and the higher SNR and sensitivity.

b- Bandwidth

The range of frequencies that the transmission could be limited to is referred to BW. The increase of the transmission bandwidth increases data rate and decreases the transmission time. LoRa BW range varies from (31.25 – 500) KHz.

c- Coding Ratio

One of the most important features that employed by of LoRa is the (FEC) forward of error detection and correction in order to improve the reliability of the link. LoRa can be configured depending on channel conditions and to be set to a specific rate. The possible available rates are 4/5, 4/6, 4/7 or 4/8 and can optionally be included in the receiver packet header [30].

3.2.2 Transmission Power

Transmission power factor is one the most important factors that affect the PDR significantly. LoRa transmission power range is between 5 to 23 dBm. However, higher transmission power increases the energy consumption of the transmission along with the SNR ratio. Throughout the practical experiments and measurements of this thesis, PDR was collected for different values of transmission power and LoRa performance was examined as well. All the reading and measurements are discussed in chapter 4.

3.2.3 Data Transmission Rate

Data rate represents the rate at which the data is transmitted from one side to another in bit per second (bps). Basically, it is the number of bits sent per second which is extremely important since it significantly affects the delivery rate of the transmission. Depending on SF and BW, the data rate of LPWAN ranges approximately between 0.3 and 27 kbps [31]. The PDR will be investigated for different data rates starting from 185 to 21875 bps in all three scenarios as we can see in chapter 4.

3.2.4 Packet Structure

There are two types of the packet format in LoRa modems, implicit and explicit. The implicit mode is simply doesn't include the header section in the packet structure and that means the CRC is set to off. Since the main concern of this thesis is to calculate the number of successfully received packets, the explicit mode is going to be used in all experiments to include the header and to set the CRC to ON.

LoRa packet structure consists of three main elements:

a. A preamble

The preamble part of the LoRa packet is used to inform and synchronize the receiver with the incoming data. The preamble is set to 8 symbols by default and it could be configured and extended.

b. Header

The header is used to provide basic information of the payload such as: payload length (in bytes), error rate and status the CRC.

c. Payload

The Payload is a variable-length that carries the actual coded message at a specific coding rate that the modem is configured with [32].

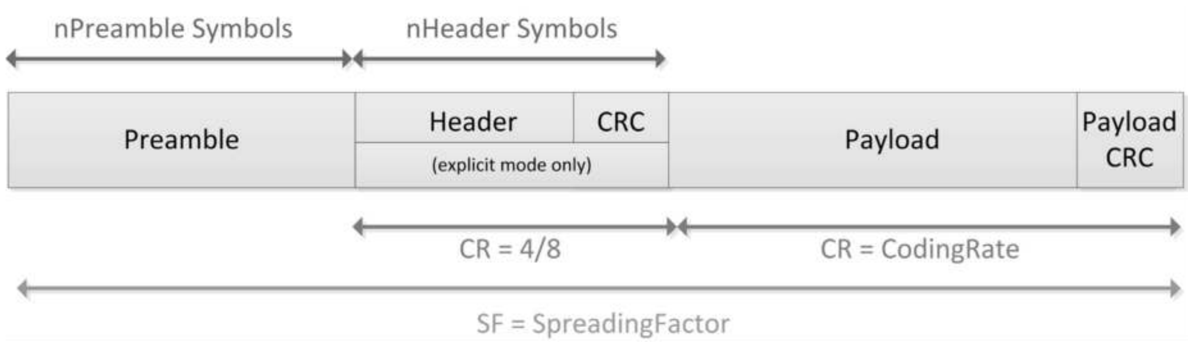

Figure 2 LoRa Packet Structure [30]

3.3 System Design and Architecture

The proposed design consists of a complete real-time measurement testing environment that consists of; sender, receiver and software environment. All these components will be discussed in details later in this chapter. The first side is the receiver mote (Rx), which is represented by a LoRa module connected to a computer through USB cable. The second side is represented by another geolocation LoRa module unit deployed on the UAV. However, the testing software environment is an Arduino software connected to a computer through a serial port which is considered as a GUI. The following graph shows the design layout and software, it shows the grounded receiver side and the deployed transmitter and the transfer mechanism of packets between the two motes.

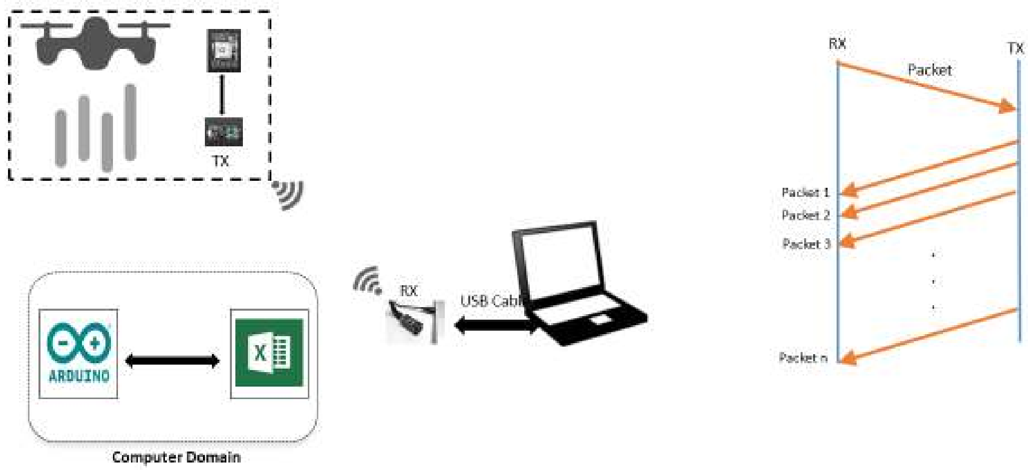

Figure 3 Design Layout

3.3.1 Hardware Modules

a. RFM95 LoRa Radio (900 MHz)

A microcontroller with a SX1276 LoRa radio transceiver has SPI interface feature and built-in USB. The chip is equipped with ATSAMD21G18 ARM Cortex M0 processor, 3.3 V boot up voltage and the clock rate is 48 MHz, power transmission capability (+5 to +20 dBm) and a u.Fl connector for external antenna, the packet radio is available with ready-to-go Arduino libraries. The modules are available for both 433

MHz and 900 MHz depending on countries ISM (Industrial, scientific and medical) bands regulations.

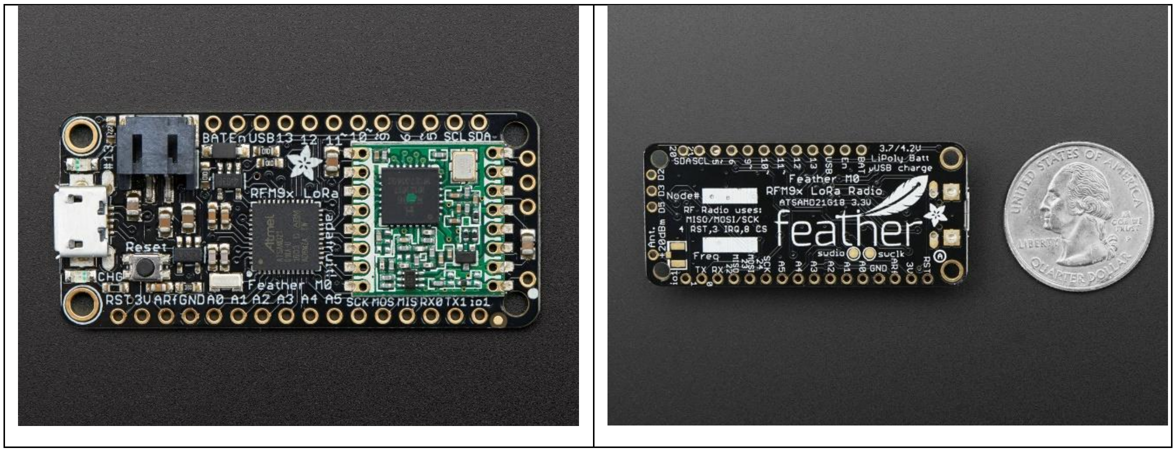

Figure 4 Adafruit Feather M0 RFM95 LoRa Radio

Feather M0 LoRa radios are not suitable for large size data transfer like audios and videos, however, they work quite well with small data packets that require long range transmission [32].

b. GPS Module

Adafruit Ultimate GPS is a 5 V friendly design and 20mA current flow with built-in data logging. It has a -165 dBm sensitivity 10 Hz update and 66 channels and internal patch antenna. It also has a u.Fl connector for external antenna. It’s a high-quality GPS module with up 22 satellites on 66 channels capability. Able to update 10 locations per second for high speed and low power usage consumption [33].

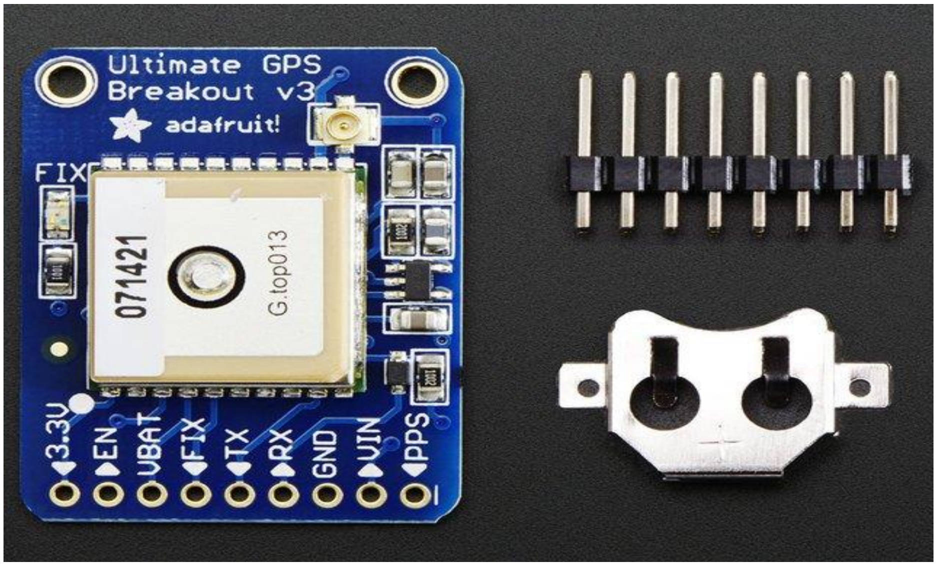

Figure 5 Adafruit Ultimate GPS

The following is the main features of the module:

Position Accuracy	1.8 meter
Velocity Accuracy	0.1 meter/sec
Start time	34 Sec
Max Velocity	515 m/sec
Dimensions	25.5mm x 35mm x 6.5mm / 1.0" x 1.35" x 0.25"
Weight	2.5 g

Table 2 Adafruit Ultimate GPS main Features

c. Antenna Kit

LoRa antenna kit was chosen for better long-distance transmission coverage. This kit fits some wireless modules like Sigfox, SiPy and BLE boards buy it also works perfectly with LoRa RFM9X radios [34].

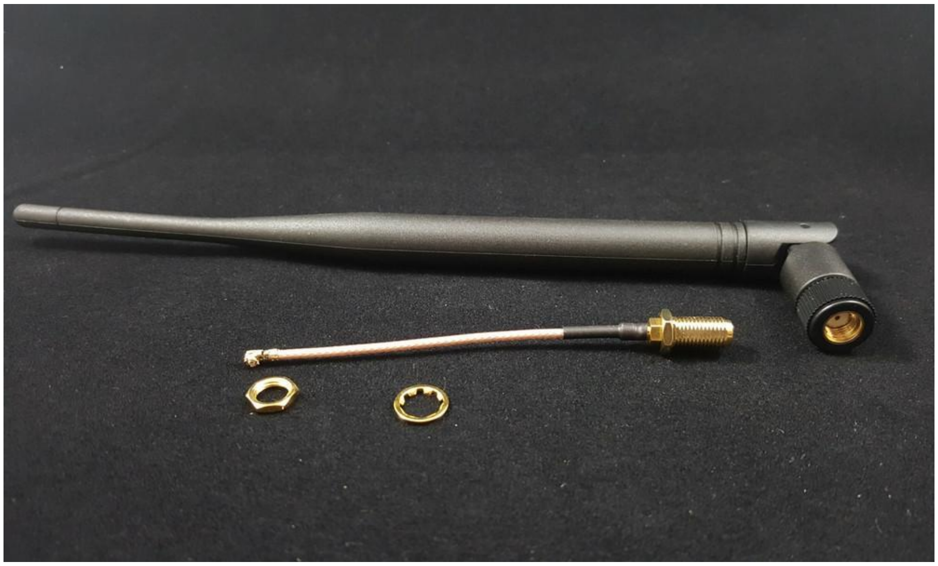

Figure 6 900 MHz Antenna Kit

The main features of the selected antenna are discussed in the following:

Frequency	900 MHZ
Antenna Type	External Antenna
RF Cable Assembly	SMA(F) JK-IPEX MHF U.FL 1.13 100MM

Table 3 900 MHz Antenna Kit Main Features

3.3.2 Receiver Mote (Rx)

The receiver side is a grounded mote consists of LoRa radio transceiver connected to a computer through a USB cable. This mote is fixed to the fence and about 3 meters high and a 900 MHz antenna is attached to it for better transmission. The picture of the receiver fixed to the fence is shown in figure (7).

Figure 7 Rx Mote

3.3.3 Transmitter Mote (Tx)

At the transmitter side, the Adafruit Ultimate GPS module is fed to the LoRa radio transceiver and both are powered by a battery as a power source. Both modules are attached with 900 MHz antennas. Table (4) shows the electronic connections between the two modules:

GPS Pin	RFM95 Transceiver
Vin	3.3 V
GND	GND
RX	TX
TX	RX

Table 4 Connection Pin

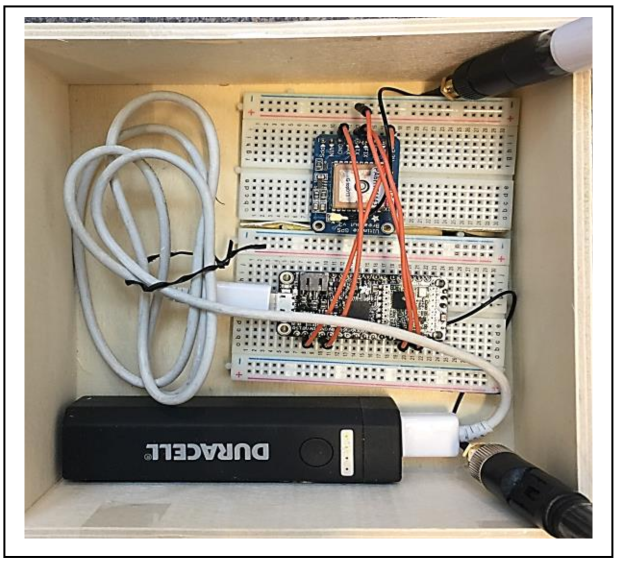

Figure 8 Tx Mote Top view

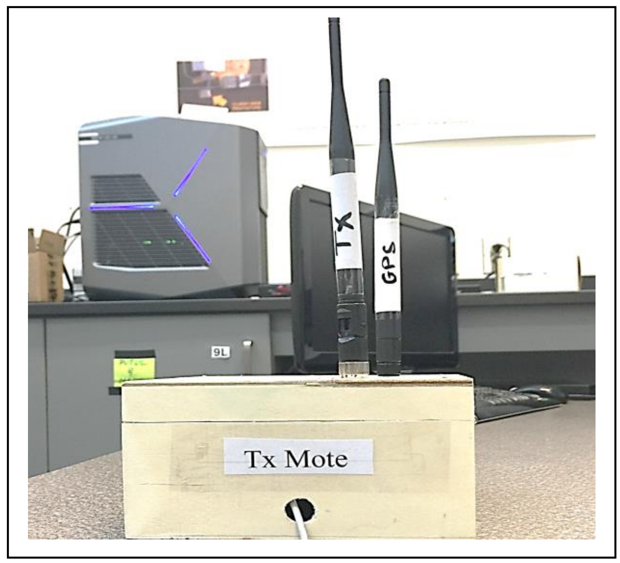

Figure 9 Tx Mote Side view

3.3.4 UAV Setup

For UAV set up, a lightweight industrial drone was used for UAV testing scenario. All hardware modules for the sender mote are mounted on the drone. Including, LoRa transceiver, GPS module and two antennas for both modules. A 5-volt rechargeable battery was also mounted on the unit as a power source in order to power the whole unit up. The transmitter side unit is shown in figure (10).

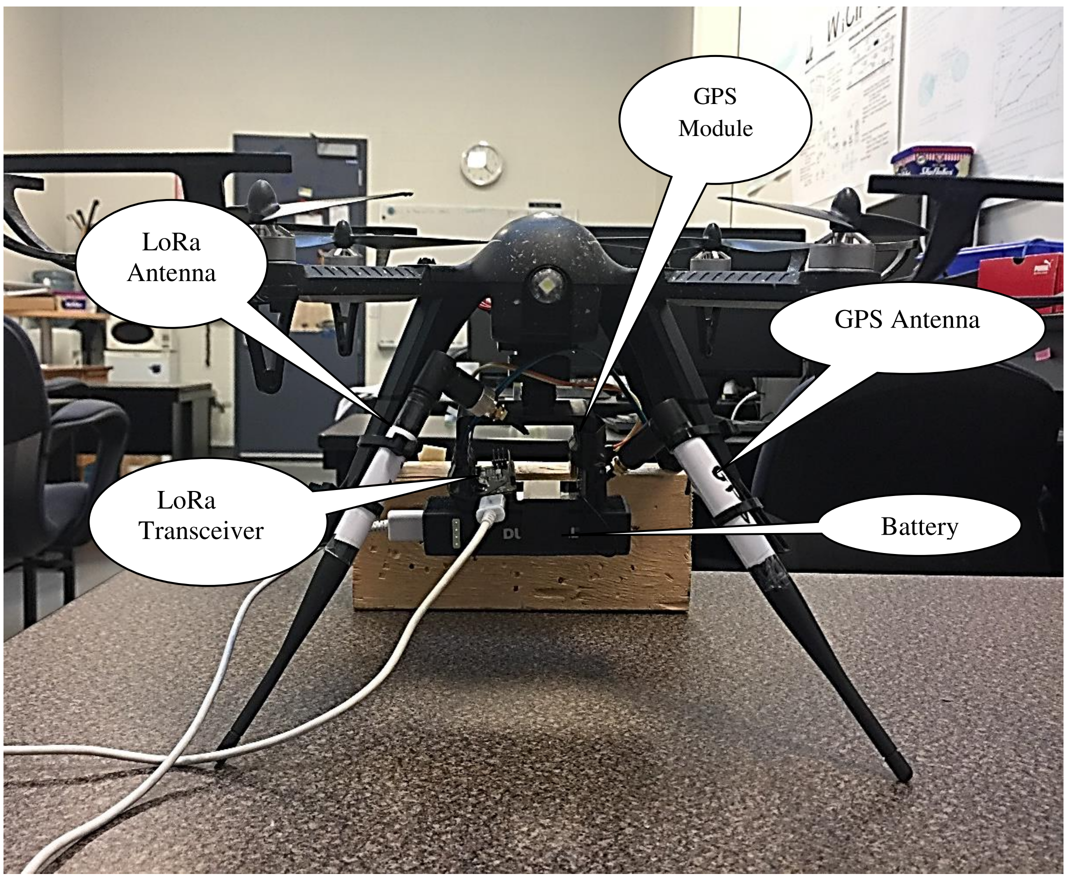

Figure 10 UAV Set up

The UAV was tested beforehand in order to check if it can handle all the extra weight added by all modules and antennas. The unit worked perfectly and was able to fly properly.

3.4 Testbed Design and Components

There were two testbeds designed for both Tx and Rx motes. The first testbed is for the receiver node which includes a LoRa transceiver fed to a computer through the serial port via a USB cable as described in paragraph 3.3.2. The second testbed is for the transmitter node, the unit includes the LoRa transceiver and the GPS module and powered by a researchable battery as described in paragraph 3.3.3. Both testbeds were programmed using Arduino open source environment [35]. Since the transmitter node was created to be mounted on the UAV, it was designed in a way to be flexible and fits a moving ends and has to be triggered by the Rx.

During experiment execution, once the Rx and Tx motes are placed and turned on, the Rx triggers the Tx mote by sending a control packet. The Tx mote testbed is programmed in a way that when the serial monitor of the receiver side is available it starts sending packets. First, it sends the coordination to inform the receiver about the UAV position. It also sends the UAV details that includes speed and altitude. Second, it sends 300 packets for each trial where the RSSI and SNR and PDR are calculated. The testbeds are able to calculate the number of successfully transmitted packets, minimum and maximum and average RSSI, minimum and maximum and average SNR, the number of successfully received packets and the number of received packets with error (packets with wrong the CRC). By specifying the number of transmitted packets at the sender side, and calculating the total number of received packets at the receiver side we can easily calculate the PDR.

$$\text{PDR} (\%) = (D/T) * 100$$

$$\text{PLR} (\%) = 100 - \text{PDR}$$

$$\text{PLR}_T = \text{PLR}+\text{PER}$$

Where: T is the total number of successfully transmitted packets by Tx

D is the number of successfully received packets by Rx

PLR_T is the packet Loss Rate

PER is the Packet Error Rate.

Figure (11) illustrates the packet structure that is used in this testbed. It consists of preamble, header .and payload. By default the preamble size configured to be 8 symbols, however, the payload size will remain variable in this testbed since the LoRa performance is going to be tested according to different payload size (different packet size). The headers are inside the LoRa's payload which is always 4 octets and 1 byte for the CRC field.

Therefore the total message length is:

Maximum Message Length = Payload size (n) – The header length (4 Octets)

Packet Size = Payload Size + Preamble Size (8 Symbols)

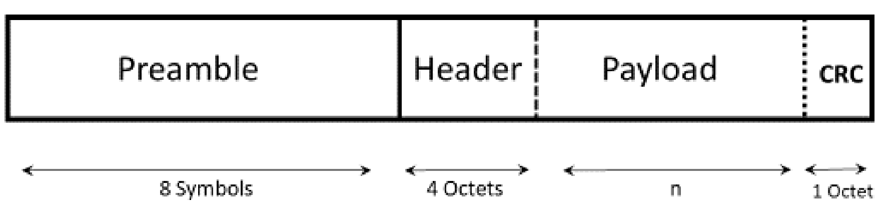

Figure 11 Testbed Packet Structure

The content of the message is not important since calculating the Bit error rate (BER) is not one of the intentions of this design. However, the content of the message will always be the UAV details as mentioned earlier in this chapter.

Up one receiving the data at the receiver side, Rx responds by notifying the sender of the required information of the last packet including the packet size. The receiver calculates the RSSI, SNR, number of received packets and the number of received bad packets. Then it prints all these information through the serial monitor provided by the Arduino software. Figures 12 and 13 show the testbed data flow chart for both sides Tx and Rx.

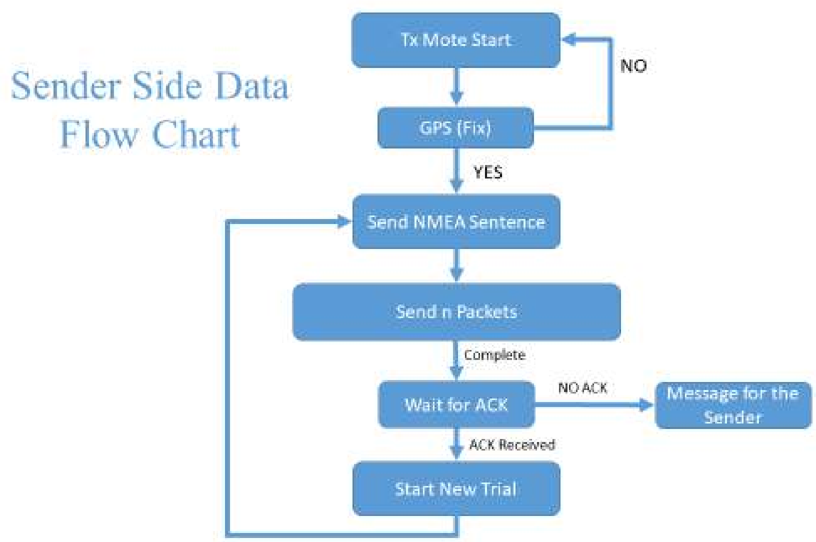

Figure 12 Testbed Data flow (Tx Mote)

Tx mote starts sending data once it triggered by the grounded receiver and after the GPS gets a fix. GPS data includes longitude, latitude, speed, and altitude of the flying drone. This information are informed as NMEA sentences and to be parsed in an ideal understandable form [33]. After accumulating the data by Tx, then Tx sends a specific number of packets which are specified to 300 packets per trial. The receiver side then waits for the acknowledgment from Rx. Rx then responds by acknowledging Tx that the packet was received successfully or it was lost or received with the wrong CRC.

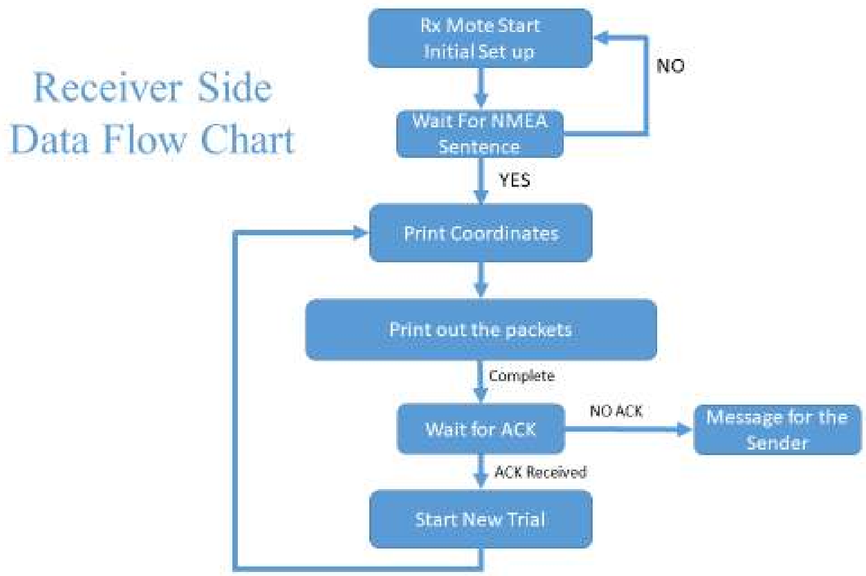

Figure 13 Testbed Data Flow (Rx Mote)

At the receiver side, Rx prints the UAV details that were sent by Tx. It also counts the number of bad packets, good packets, RSSI and SNR of the last received packet.

3.5 Testing Environments

In this section, the experimental environments, procedures, and results will be provided, along with clear representation about the nature of each environment and test sites. Several sites were chosen to be the ideal candidates with taking into consideration the NOLS and LOS nature of these sites. Real-time measurements were collected at each site.

3.5.1 Line-of-Sight (LOS)

For LOS, a 400 meter part of Ojibway street in the south-west of Windsor city, southern Ontario, Canada was considered to be the ideal site since it is an urban area and a straight line with no obstacles between the Tx and Rx. Trials were done with the Rx located at the corner of the intersection of California street and Ojibway as shown in figure 11. However, the Tx was moving part were the measurements collected depending on the testing scenario.

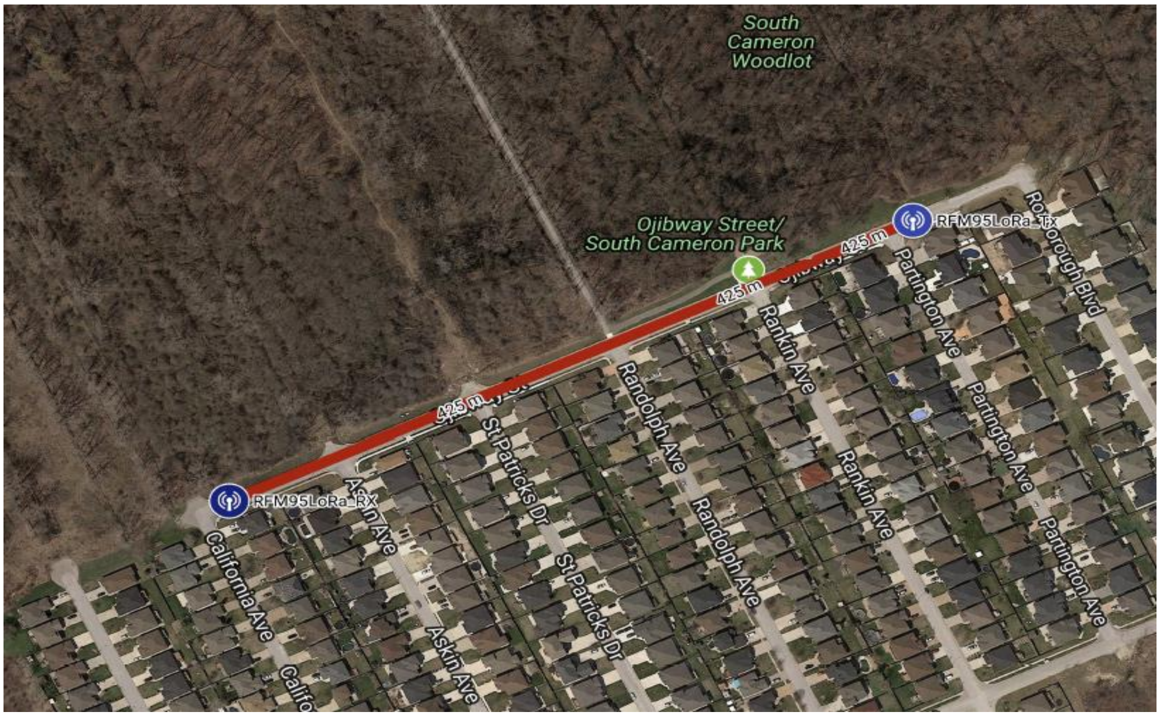

Figure 14 Ojibway

3.5.2 Non-line-of-Sight (NLOS)

The NLOS measurements were conducted in Devonwood Conservation Area, South of Windsor, Ontario, Canada. This conservation area is a unique woodland located in an urban center of Windsor city. It features more than 4.5 Kilometers of wild trials and about 38 hectors of forest [36]. This site was selected to be the NOLS testing site due to its bushy nature and its big trees. The Rx was placed in the parking lot of the park as shown in figure 12 and the Tx was located in different places depending on testing scenarios.

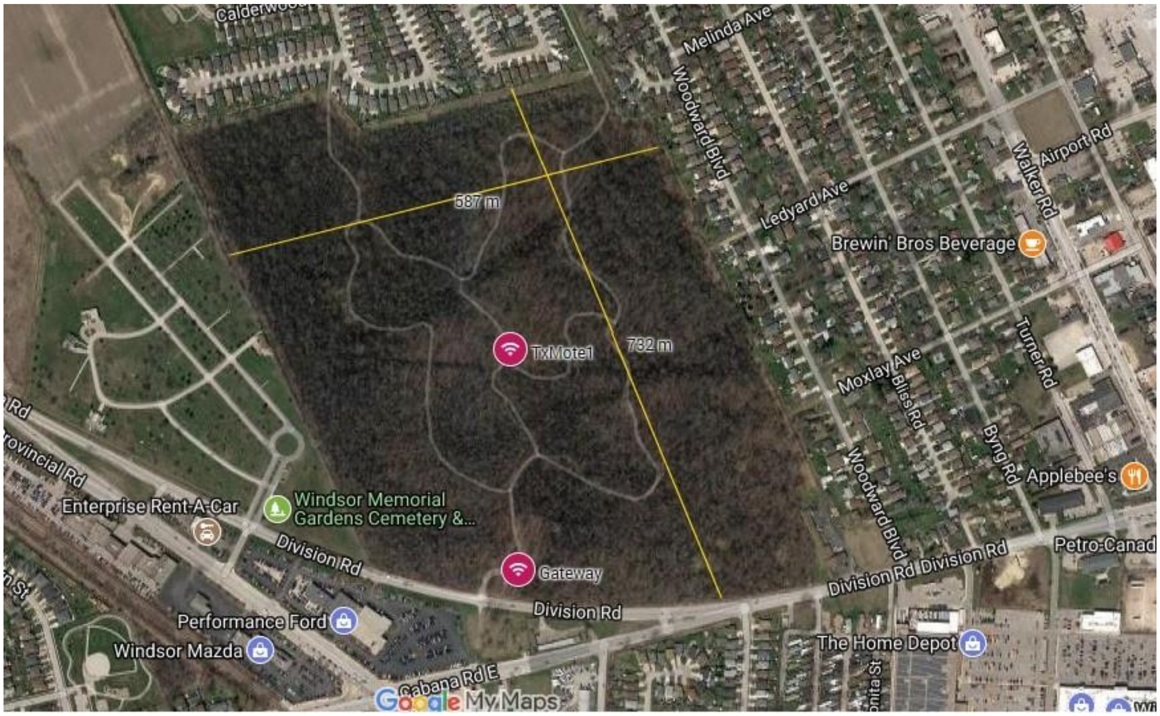

Figure 15 Devonwood Conservation Area - South of Windsor

3.5.3 UAV Testing Site

For UAV testing, the experiment was conducted at the soccer field of the St. Denis Athletic & Community Centre, University of Windsor, Ontario, Canada. It is considered as a LOS environment since no obstacles between the sender and the receiver. The testing site is shown in figure (16).

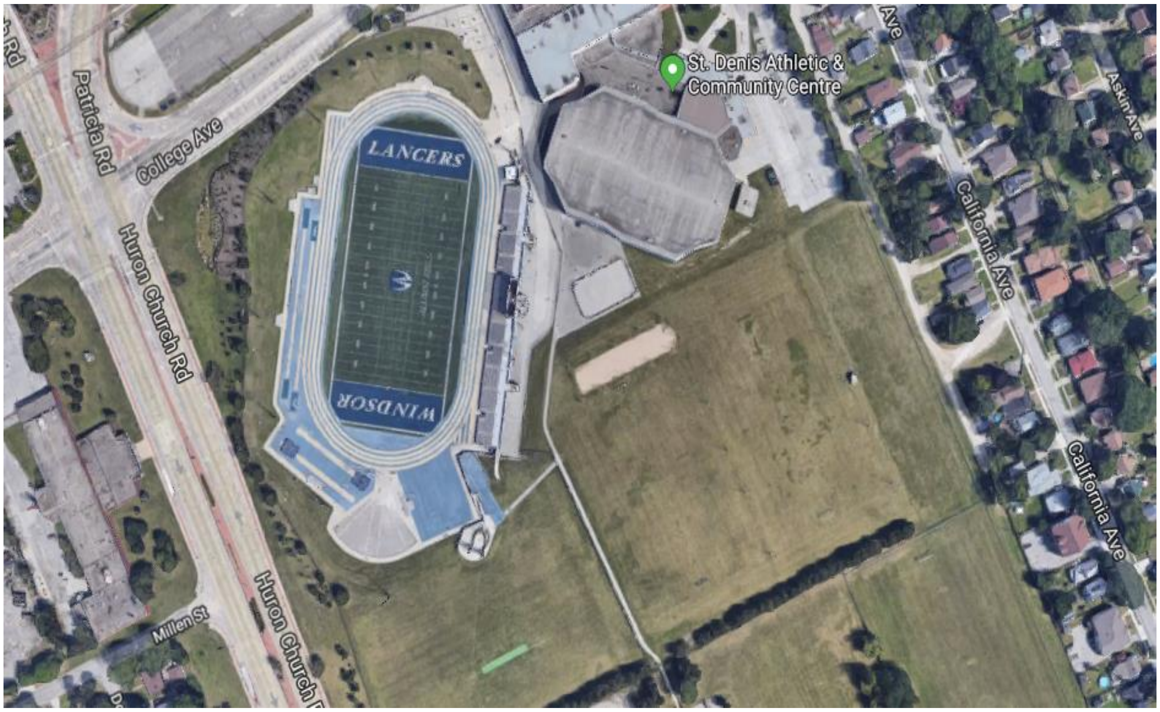

Figure 16 UAV Testing Site

3.6 Summary

A LoRa-LPWAN system design and methology are well explained in details throughout this chapter including all the hardware devices and software environments designs. All suggested modules were tested before hands to ensure reaching the goals. These hardware modules were discussed in details in this chapter. However, Testbed components are revealed thoroughly for both sides the transmitter and receiver as well. And finally, the testing environments and sites where the tests took place were located and briefly illustrated.

4. TESTING AND RESULT ANALYSIS

4.1 Introduction

After defining the main parts of the of the proposed design and system methology along with the main aspects and structure of the testbed that is going to bed used to test the system performance and the reliability of the communication scheme prototype in chapter 3, in this chapter, the practical measurements and results are going to be discussed. This chapter focuses on the investigation of the scheme performance in different scenarios to examine its capabilities and to check how it behaves in special environments and under special circumstances in order to show its abilities to fit this particular uses. These testing scenarios include changing the main physical layer factors such as the transmitted power, data rate, and the UAV speed.

In order to do that, the testing must take place in both testing environment, LOS and NLOS. For UAV speed test, the test was done in the LOS environment only since it hard to release the drone in the forest due to the big trees and hard accesses.

Different types of measurements are going to be discussed in this chapter. First, the PDR that is discussed in the earlier chapters. Second, minimum, maximum and average RSSI in (dBm) to show the average signal strength that was collected during the conduction of the experiments of each scenario. Finally, the minimum, maximum and average SNR ratio is going to be discussed in (dB) which is also an important factor especially in urban LOS environment.

4.2 Test Scenarios and Results

4.2.1 Transmission Power Vs PDR

The PDR was examined when the transmission power of both the transmitter and the receiver varies between 5 dBm and 23 dBm for both testing LOS and NLOS testing sites. The LoRa transceivers of the two motes where configured with the same factors values (SF=7, CR=4/5, BW= 125 KHz) which is considered as a medium range, with 50 byte payload size. The PDR was examined for four transmission power values; 5, 11, 17 and 23 dBm. The following graphs show how the PDR changing when the transmission power varies.

A. Test Run 1: (NOLS Environment)

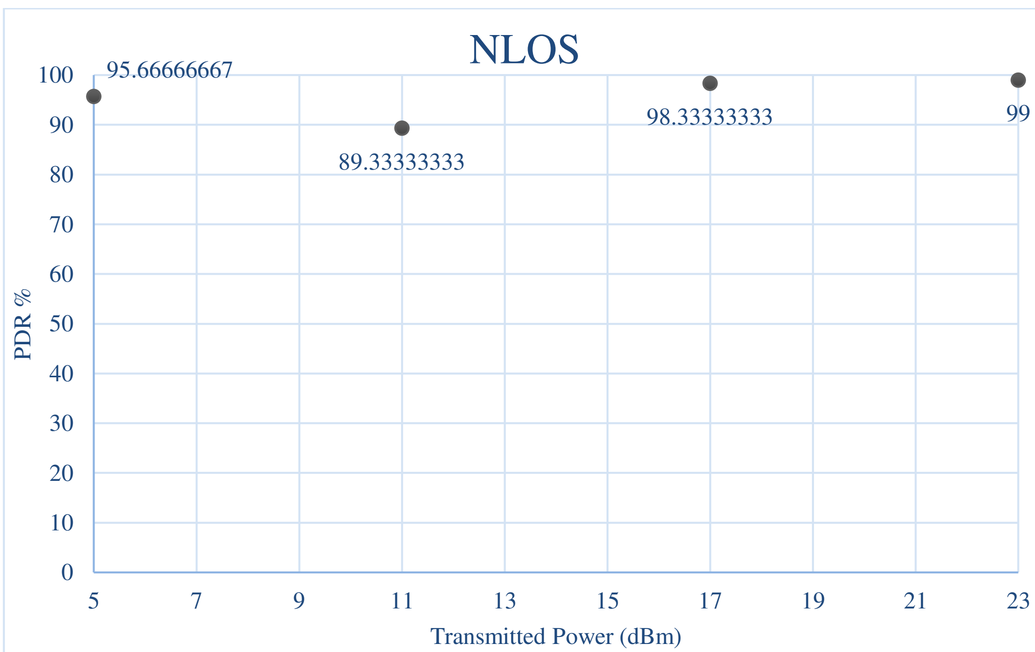

Figure 17 Test Run 1

For NOLS, figure (17) reveals that when the transmission power is 5 dBm, PDR is about 95 % and that is an excellent percentage especially with this low power and in NLOS environment where the distance between the transmitter and the receiver was about 285 meter. It also shows that the percentage increases slightly as the power raises until it reaches its highest value at 23 dBm where almost all the packets were delivered successfully.

B. Test Run 2: (LOS Environment)

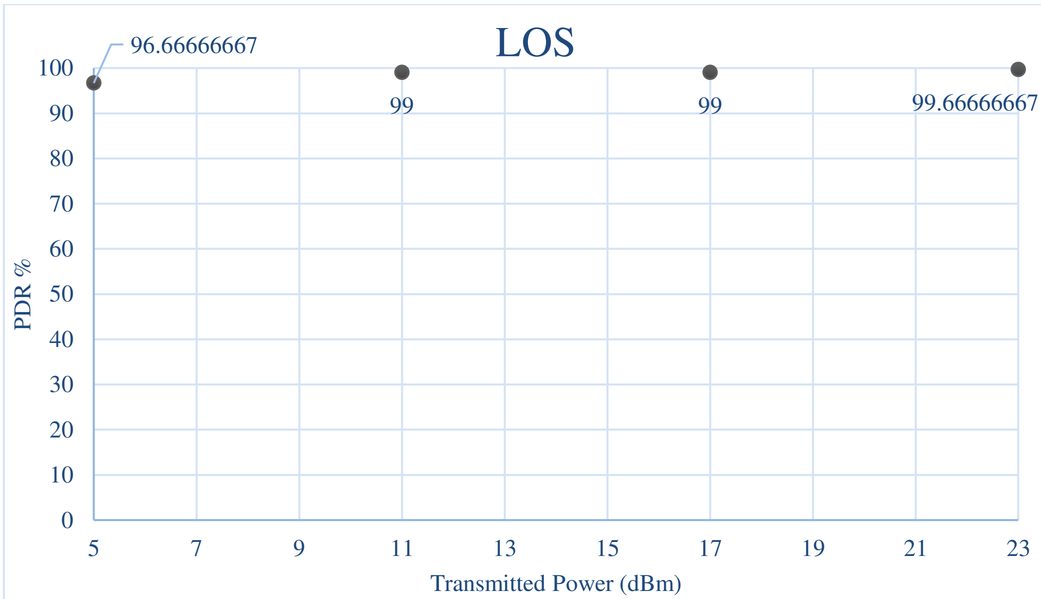

Figure 18 Test Run 2

For LOS, figure (18) shows even better results since it’s a LOS environment. The figure shows that the rate was always high as 99% except for 5 dBm which it was about 96 % for 300 meter distance between the transmitter and receiver.

4.2.2 Data Rate Vs PDR

Data transmission rate is another important factor that plays an important role in LPWAN technologies performance. The value of data rate is critical and should be examined in this study in order to cover all the possible changes in LoRa capabilities. LoRa was investigated in the same NLOS and LOS environments to study the direct effect of the data rate. First, we should understand how LoRa data rate is measured and configured. For that, [37] presents a LoRa modem calculator tool that allows quick evaluation of the data rate and on-air time transmission calculation, this tool is free of charge and could be downloaded from [27].

The figure below shows how this tool is structured and the main configuration factors the need to be specified in order to set the required bit rate in (bps) and to estimate "Time on air".

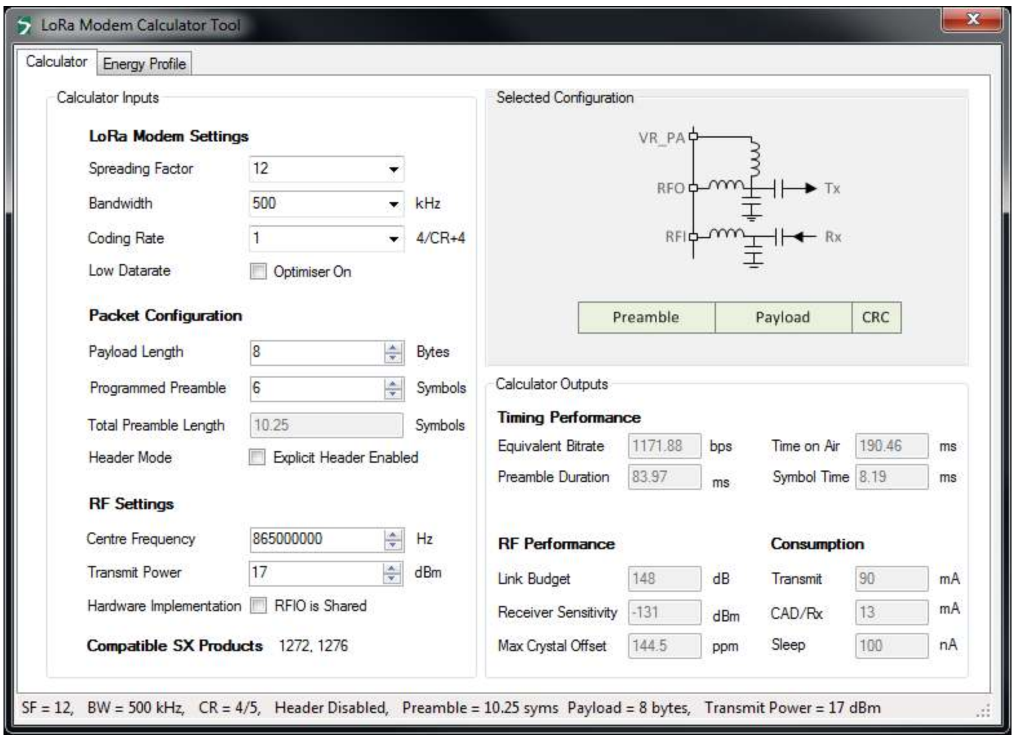

Figure 19 LoRa Calculator

For the conducted experiment the following table shows the PHY and other values:

PHY			Center Frequency	Payload length	Preamble length	Tx power	Evaluated Data Rate
SF	BW (KHz)	CR					
12	125	4/8	915 MHz	50 Byte	8 Symbols	20 dBm	184 bps
9	31.25	4/8					275 bps
7	125	4/5					5470 bps

7	500	4/5					21875 bps

Table 5 PHY Factors and the evaluated Data Rate

A 300 packet of data was sent by the transmitter side. Four different values of the data rate were tested as shown in table (5). Results show that using less data transmission rate allows more packets to be delivered successfully. For instance, with 184 bps, the PDR was almost 100% for both LOS and NLOS. For NLOS, the PDR decreases gradually until it reaches the minimum which was about 90% for 21875 bps, see figure (20). On the other hand, for LOS there was a slight difference in PDR when the data rate changes and that could be caused by the less complexity of this environment since it's a straight line communication and no obstacles between the two modems.

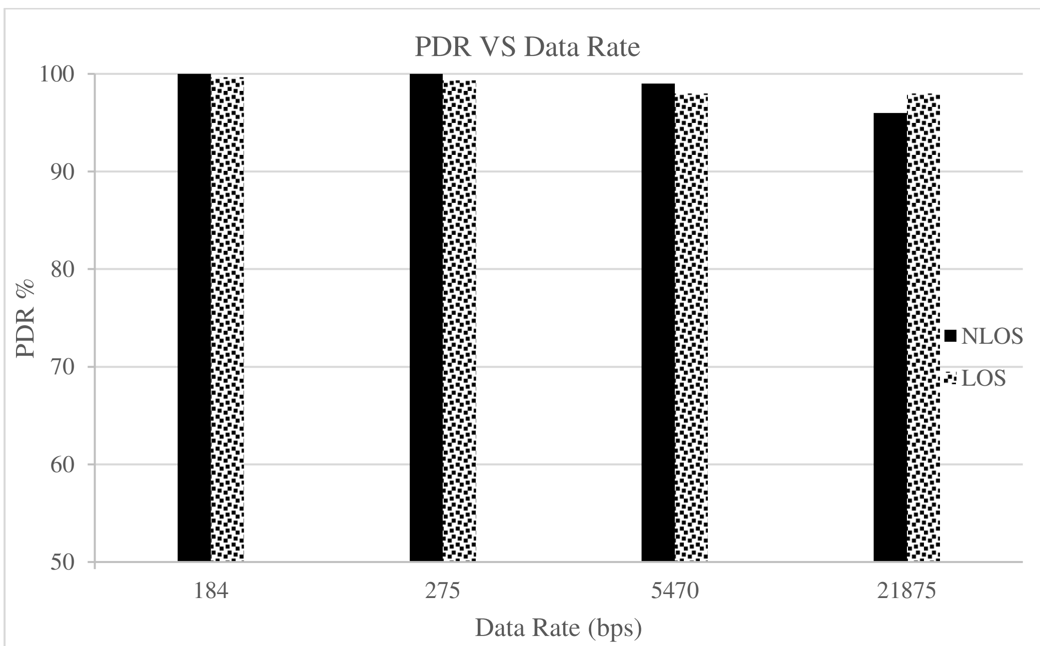

Figure 20 Test Run 3 and 4

This unusual changes might be caused by two possible elements; first, the more interference and noise in the urban area that is caused by different frequency ranges used by homeowners such as satellite or other radio frequencies. Second, there is a possibility of a setup error.

4.2.3 Distance Vs PDR

In this test, PDR was examined for 400 meter distance between the sender and the receiver and the measurements for the PDR were taken every 50 meters. The transmission power was set to a moderate value which is 17 dBm. The test took place at Ojibway street and the environment was LOS only.

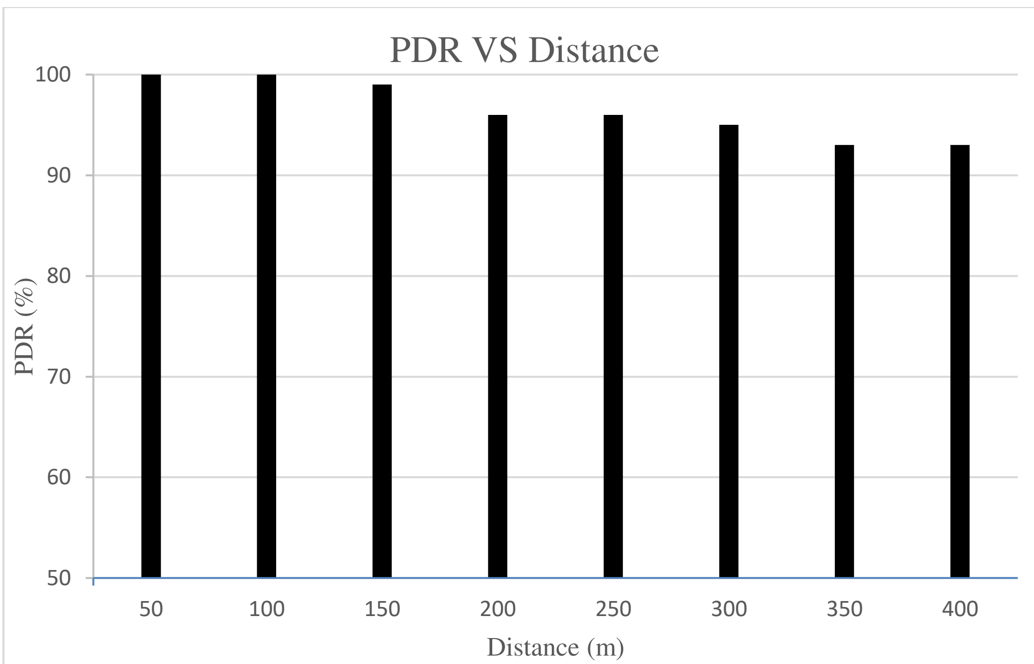

Figure 21 PDR Vs Distance

From the graph above, the readings are quite acceptable where the PDR is always above 90% even for about 400 meters distance between the Tx and Rx. And that reveals the long range successful of the LoRa technology.

4.2.4 UAV Speed Vs PDR

A. Test Run 5 :

The first test run was conducted with 21875 bps data rate at St. Denis soccer field south campus of the University of Windsor which is considered as a LOS environment. Since the drone used was not able to maintain the same speed, the average speed was fluctuating between 20 to 31 Km/h. Only 140 packets were sent per trial because the flight time of the drone used was limited to about 10 minutes. About 134 packets were successfully received at the receiver mote.

Average UAV Speed (Km/h)	**PDR (%)**
20 – 31	97.10

Table 6 Test Run 5

B. Test Run 6 :

The second test run was conducted for 5470 bps with the same procedure as run test 1. For less data rate, the PDR was higher as 99.25 %.

Average UAV Speed (Km/h)	**PDR (%)**
20 – 31	99.25

Table 7 Test Run 6

4.3 Summary

The communication scheme prototype showed an excellent performance and LoRa transceivers were excellent candidates for this purpose. The performance investigation of the proposed prototype shows authentic accurate measurements for all testing sites. For

NOLS testing, the measurements show that the reception of data was about 95%. However, the PDR was even better with all configuration changes.

For LOS measurements, the readings showed some kind of unstable and unpredictable measurements. In that, one of the main causes could be the interference and noise caused by a different wide range of frequencies used by homeowners in urban areas. The 900 MHz band is a portion of UHF radio spectrum which is most likely suggested to be the main reason, also the experimental setup could be a secondary cause too.

For the UAV speed testing, LoRa was able to deliver data with a maximum speed which was about 37 Km/h and the altitude of the drone was about 30-40 meters above the ground. In general, the testbed readings prove that the prototype fits perfectly for this environmental monitoring system.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

A practical and reliable high packet delivery rate communication scheme prototype for UAV environmental monitoring system was developed and IOT hierarchical communication topology involving IOT modules was proposed. The two motes of the scheme were able to communicate with each other using a LPWAN technology protocol. The proposed prototype consumes very low power and requires a very simple power source like a battery. The two nodes communicate through different environmental conditions and under special circumstances. For this purpose, a developed valid testbed was able to calculate all the required measurements in order to evaluate the functional proposed system. In each trial, a specific number of packets was sent from the sender side and the successfully received packets were collected and monitored at the receiver side.

A LoRa-LPWAN testbed was also developed to determine the system's ability to perform using a drone where all the modules were mounted on the flying UAV. The drone was traveling at a decent pace which was about 20-30 Km/h and around 20 meters high. The receiver side was grounded and 2 meters high antenna was attached. An impressive PDR was collected which exceeded 95 % for both 21875 and 5470 bps for the same testing setup. These readings collectively demonstrate that LoRa devices are able to perform suitably with the UAV monitoring systems.

5.2 Future Work

For future work, many more features could be added to this proposed design, since it is a first complete prototype. These features would make it more efficient and powerful. These features and ideas could be summarized in a list and would be a proper start for further studies and future developments:

1. The BER could be added to the testbed in order to evaluate the exact error rate and then the bit error location.
2. Adding more grounded nodes where each node contains a verity of both digital and analog sensors. Each node should then specified with a specific address to increase the measuring area.
3. Adding more nodes might require using different protocols. And MQTT (Message Queuing Telemetry Transport) could be the first option in this case.
4. Developing the testbed to increase the measurement features, for example measuring the power consumption that the transceivers consume in each trial.
5. To further expand of the network size, it might be necessary to add another gateway and that requires developing a protocol that can handle that expansion.
6. Developing a GUI to make the system user-friendly.

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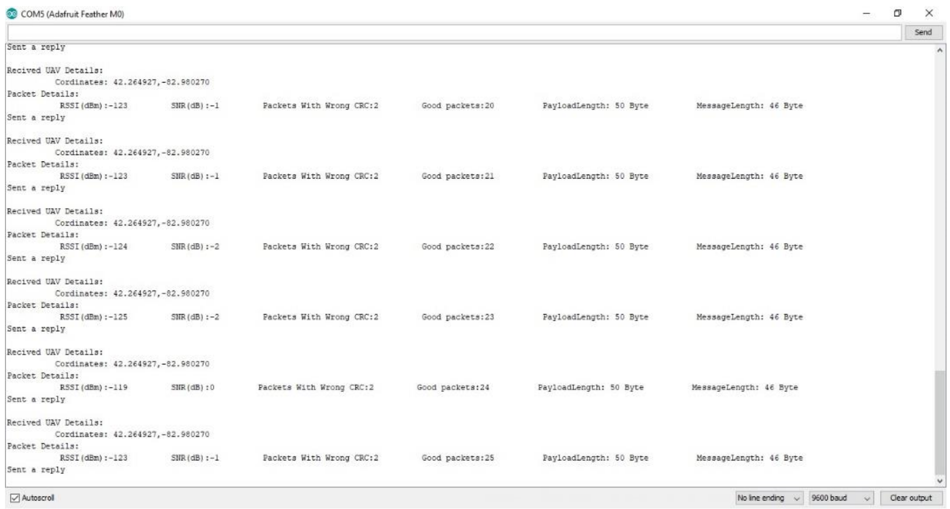
APPENDIX

A. Testbed Serial Monitor



B. Testbed Serial Monitor

C. NLOS Transmitter Node

D. LoRa Testbed Results Chart

LOS Test								
Tx Power	Transmitted Packets	Received Packets	Min.RSSI (dBm)	Max. RSSI (dBm)	Average RSSI (dBm)	Min.SNR (dB)	Max SNR (dB)	Average SNR (dB)
5	300	290	-117	-115	-115.16	-1	3	1
11	300	297	-115	-113	-114.33	3	5	4
17	300	297	-114	-109	-111.91	4	7	5.5
23	300	299	-111	-106	-109.08	6	10	7.91
NLOS Test								
5	300	287	-125	-119	-122.33	1	3	2
11	300	268	-123	-119	-117.16	-1	1	0
17	300	295	-119	-118	-116.25	3	4	2.5
23	300	297	-113	-116	-123.33	3	6	4.5

E. LoRa Testbed Results Chart

LOS Test								
Data Rate	Transmitted Packets	Received Packets	Min.RSSI (dBm)	Max. RSSI (dBm)	Average RSSI (dBm)	Min.SNR (dB)	Max SNR (dB)	Average SNR
184	300	293	-121	-106	-114.08	0	10	7.8

275	300	297	-115	-107	-110.83	6	9	7
5470	300	291	-111	-106	-108.83	6	10	7.83
21875	300	294	-118	-105	-111.66	-2	2	0.16
NLOS Test								
184	300	298	-113	-106	-108.5	5	9	6.83
275	300	295	-114	-106	-109.41	4	6	5.16
5470	300	287	-116	-113	-114.08	3	6	4.5
21875	300	275	-122	-113	-116.91	-7	-2	-4.66

F. LoRa UAV Speed Testbed Results Chart

UAV Speed	Transmitted Packets	Received Packets	Min.RSSI	Max. RSSI	Average RSSI	Min.SNR	Max SNR	Average SNR
184 bps								
	No Reception							
275 bps								
	No Reception							
5470 bps								
Ave.Speed (20-31) Km/h	135	134	-96	-68	-75.37	9	12	9.61
21875 bps								
Ave.Speed (20-31) Km/h	138	134	-99	-60	-71.68	3	6	5.23

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