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Performance Evaluation of Long Range (LoRa) Wireless RF Technology for the Internet of Things (IoT) Using Dragino LoRa at 915 MHz

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Performance Evaluation of Long Range (LoRa) Wireless RF Technology for the Internet of Things (IoT) Using Dragino LoRa at 915 MHz

by

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A thesis submitted to the School of Engineering in partial fulfillment of the requirements for the degree of
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THESIS CERTIFICATE OF APPROVAL

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ABSTRACT

Internet of Things (IoT) is a developing concept that introduces the network of physical sensors which are interconnected to each other. Within this smart environment, smart objects use the inter-connectivity to process, communicate, and exchange data among themselves without any human interaction. Some sensors are wirelessly connected among themselves and to the internet. Currently, IoT applications demand substantial requirements in terms of Radio Access Network (RAN) such as long-range outdoor coverage, environmental factors, obstructions, interference, power consumption, and many others. Also, the current wireless technologies are not able to satisfy all these requirements simultaneously. Therefore, there is no single wireless standard that would predominate the IoT. However, one relevant wireless radio solution to IoT is known as Long Range Wide Area Network (LoRaWAN), which is one of the Low Power Wide Area Network (LPWAN) technologies [1]. LPWAN has appeared as a significant solution to offer advantages such as long-range coverage connectivity with low power consumption, an unlicensed spectrum, and affordability. Most likely LoRa with the inherent long-range coverage and low power consumption features will become the *"go-to"* technology for IoT applications [2]. LoRa is a novel solution that is attracting considerable attention for both academic and industrial purposes [3, 4].

For that reason, the proposed research entails the feasibility analysis and performance evaluation of LoRa communication focusing on the physical layer, which involves the radio configuration parameters such as ***Spreading Factor*** (SF), ***Signal Bandwidth*** (BW), ***Coding Rate*** (CR), and ***payload size***. This experimental work includes connecting to different IoT servers in the cloud, such as ***"The Things Network"*** (TTN), ***"ThinkSpeak"***, and integration with ***"Cayenne"***. Therefore, ***348*** (120 first + 228 second test) different configurations are carried out among SF, BW, CR, and payload in order to measure the impact on ***Time-on-air*** (ToA). When a payload size of 25 bytes (2 sensors) was connected to the ThingSpeak server, only ***57*** out of 120 configurations met the FCC's requirement on ToA ($<$ ***400 ms***) [5]. It was observed that the number of configurations reduced further to ***23***, when the payload size was increased up to ***118 bytes*** (10 sensors).

Chapter 1
Introduction

The increase in the number of low power wireless technology devices has brought a revolution in the past few years. It is expected that more than 50 billion devices will be connected to the internet by wireless networks. The interconnection is more frequent among "things" to the internet, making the "Internet of Things" (IoT) increase in popularity every day. Wireless communications are the future to connect things to the internet and this becomes more demanding during the transition period from the fourth-generation wireless network to the fifth-generation network. One prominent technology for the IoT is *LoRa* (*Long-Range*) technology, which is provided by the 3rd Generation Partnership Project (3GPP) group and is specially designed for low-power and long-range wireless communication. LoRa is one of the Low Power Wide Area Network (LPWAN) technologies, based on the spread spectrum technique. This technology is suited for the applications that requires the transmission of low data rate over longer distances. Some of the LPWAN technologies include LoRa, Sigfox, and Narrow Band (NB)-IoT. A comparative study of LPWAN technologies was carried out by Kais Mekki et al. and is presented in Figure 1.1. They showed that LoRa and Sigfox have benefits in terms of long-range, capacity, cost, and battery lifetime. In contrast, NB-IoT is advantageous in terms of quality of service and latency [6]. Also, LoRa has prominent benefit for coverage range (roughly 10 km depending on line-of-sight) over other wireless technologies such as short-range Wi-Fi, Bluetooth, Zig-Bee, and long-range cellular communications. Figure 1.2 shows the comparison of maximum theoretical range and data rate for various wireless technologies [7].

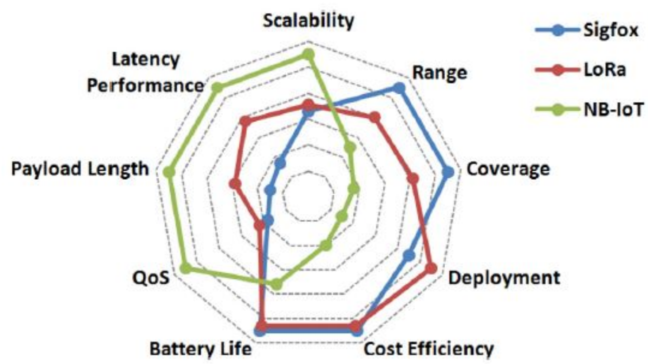


Figure 1.1: Comparison of LPWAN Technologies [5]

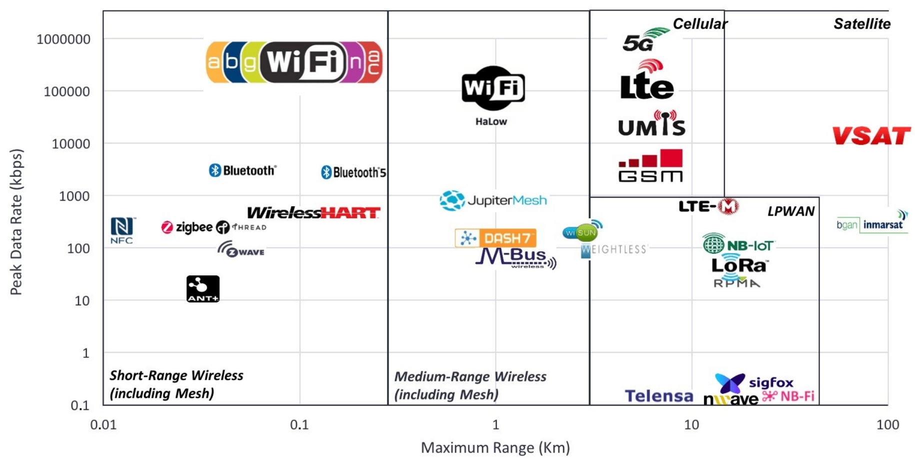


Figure 1.2: Comparison of Wireless Technologies - Peak Data Rate vs. Maximum Range [6]

LoRaWan was developed in 2012 and the standard of LPWAN is made by LoRa Alliance with the LoRaWAN® specification which defines all the protocols to ensure interoperability among devices [8]. LoRa Alliance members include brands such as Semtech, Cisco, IBM, Foxconn, Sagemcom, and HP as well as companies such as Bosch, Schneider, Mueller, and Diehl. The LoRa wireless module (radio chip) is developed by Semtech [9]. LoRaWan technology can be operated at an unlicensed ISM (Industrial, Scientific, and Medical) radio bands. LPWAN in other parts of the world, each country defines its own operating frequencies of LoRa. For example, United States is from 902-928 MHz (usually called band of 915 MHz); Europe operates from 867-869 MHz (868 MHz); China from 470-510 MHz (433 MHz); Korea and Japan from 920-925 MHz; and India from 865-867 MHz [10]. This experimental work applies to ITU region 2 only (902-928MHz).

1.1 Motivation

LoRa technology provides considerable advantages, such as long-range, battery lifetime, and affordability [11]. The primary motivation of this proposed research is based on the inherent features of the physical layer of LoRa. The feature of LoRa is long-range (theoretically 10 km) coverage with a very low cost which is not achievable by other technologies such as Wi-Fi, Bluetooth, Zigbee, etc. That is why LoRa is attracting considerable attention for both academic and industrial purposes. The coverage range depends on path loss and susceptibility to interference. In other words, the presence of obstruction, urban density (dense urban, urban, suburban, and rural) can impact the performance of LoRa. In addition, LoRa has the best radio ***Link Budget*** (a typical value of 157 dBm) of any other standardized wireless communication technologies [10]. The link budget represents the quality of a radio transmission channel and can be computed by subtracting the max Receive (Rx) Sensitivity from max Transmit (Tx) Power, which is calculated by the Eq (1.1). Theoretically, the Rx sensitivity is computed by the Eq. (1.2) [12].

$$Link\ \ Budget\ \ (dB) = Tx.\ \ Power\ \ (dB) - Rx.\ \ Sensitivity\ \ (dB) \tag{1.1}$$

- Link Budget = Maximum Link Budget (dB)
- Tx. Power = Maximum Transmission Power (dB)
- Rx. Sensitivity = Minimum Receive Sensitivity (dB)

$$Rx.\ \ Sensitivity = -174 + 10\log_{10}(BW) + NF_{LoRa\ transceiver} + SNR_{Limit:\ for\ each\ SF} \tag{1.2}$$

- BW = Bandwidth in Hz
- NF = Receiver architecture Noise Figure (6 dB) for LoRa transceiver chip SX1276
- SNR = Signal to Noise Ratio Limit in dB (depends on SF)

Dragino LG01 gateway has Semtech's transceiver SX1276 that has a NF= 6 dB. The datasheet of SX1276 LoRa Transceiver is provided in appendix A. The SNR limit is -20 dB for SF = 12. Increasing the *SF* for each value, the SNR Limit also changes by -2.5 dB. Furthermore, the Dragino gateways have the maximum transmitter power = 20 dBm and the default value of bandwidth is 125 KHz [13]. Figure 1.3 explains the relationship between link budget and receiver sensitivity, as well as details the calculation of received power. For all SF, the receiver sensitivity calculations is presented in Table 1.1 which considers BW = 125 KHz and NF = Receiver architecture Noise Figure of 6 dB [14].

$$Rx.\ \ Sensitivity = -174 + 10\log_{10}(125000) + 6 - 20 = -137dBm \tag{1.3}$$

The link budget is computed by Eq. (1.1).

$$Link\ \ Budget = -137dB - 20dB = -157dB \tag{1.4}$$

The expression of received power in wireless communication involves addition of all the gains provided the transmitter/receiver and subtraction of all the losses experienced during path propagation [15].

$$ReceivedPower(dBm) = TransmittedPower(dBm) + Gains(dB) - Losses(dB) \tag{1.5}$$

The received power on wireless communication is mainly affected by path loss, which depends on distance, frequency, obstruction in the propagation path and structural attenuation. Figure 1.4 shows the typical attenuation on 900 MHz frequency [16].

Furthermore, LoRa is operated an unlicensed ISM radio frequency bands (902 MHz to 928 MHz in the United States); therefore, the operator is not required to apply for a license at FCC to use the radio frequency. Also, signal security is another vital motivation provided by LoRaWAN technology as it provides end-to-end *security* with AES[1] cryptographic algorithms.

[1] AES - Advanced Encryption Standard. "It is a public encryption algorithm based on symmetric secret keys, allowing message encryption and authentication." [17]

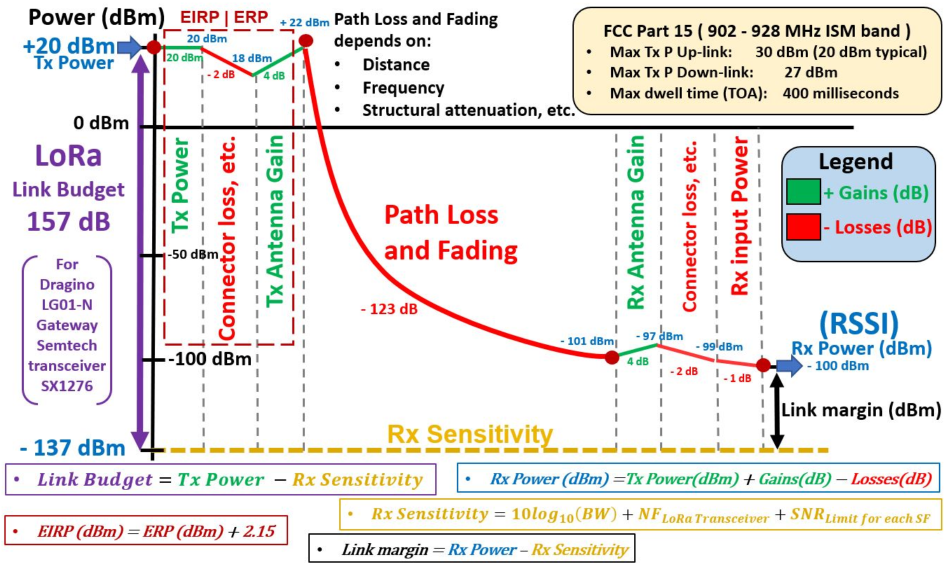


Figure 1.3: Relationship Between Link Budget and Rx Sensitivity [14]

Table 1.1: Theoretical values of SNR limit for various SF

SF	Chips / Symbol	SNR Limits (dB)	Rx. Sensitivity
7	128	-7.5	-125 dBm
8	256	-10	-127 dBm
9	512	-12.5	-130 dBm
10	1024	-15	-132 dBm
11	2048	-17.5	-135 dBm
12	4096	-20	-137 dBm

They provide a secured payload with 128 bits from the LoRa end device to the end cloud server. LoRaWAN principally employs two keys of security with 128-bits per key: (1) for the network called *Network Session Key* (NwkSKey) and (2) for the application called *Application Session Key* (AppSKey). The *Network Session Key* guarantees the authentication of the device in the network; on the other hand, the *Application Session Key* guarantees that the network operator cannot access the information sent by the device (users' application data) [10]. Other identifiers are *Device Address*, Device EUI (DevEUI) which is an end-device serial unique identifier, and Application EUI or Application Server identifier [18].

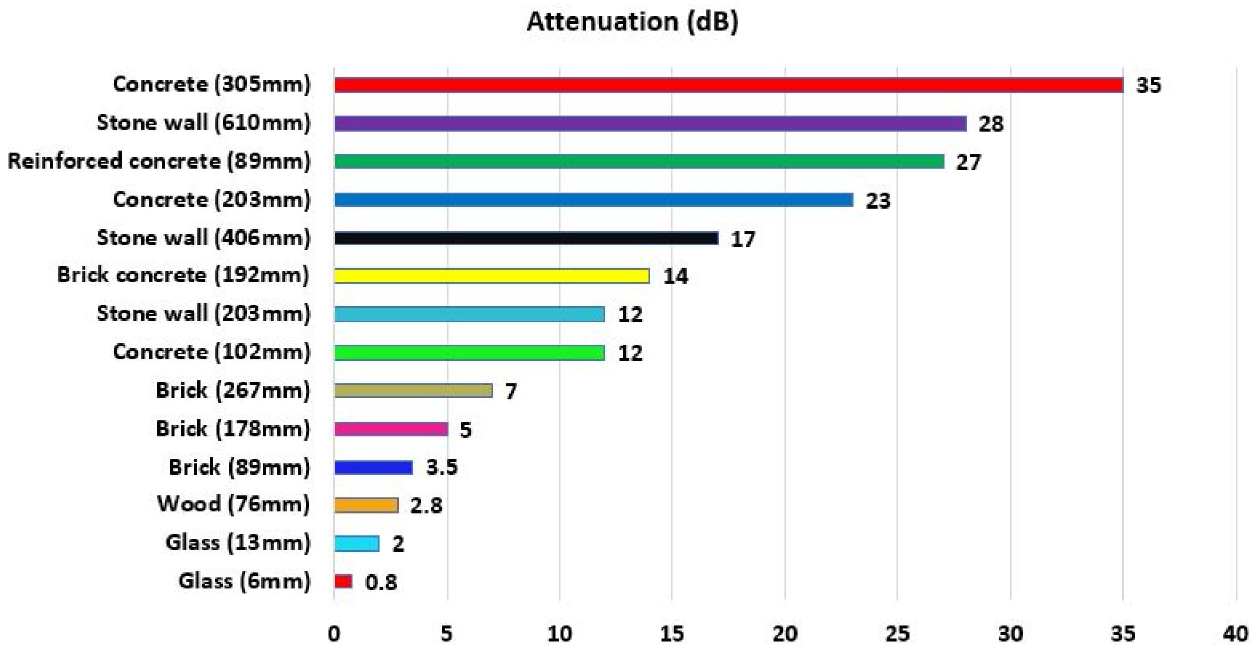


Figure 1.4: Typical Attenuation on 900 MHz Frequency by Different Materials [14]

The following is a summary of the key features of LoRa.

- Long-range coverage (roughly 10 km depending on line-of-sight) with *low power*
- The best *link budget* of any other standardized wireless communication technologies
- Operates under unlicensed frequency ISM bands
- Security (end-to-end AES 128 encryption)
- Geo-location (GPS tracking applications)
- Mobility (communication with devices in motion)
- Lower power for operation (requires minimal energy to Transmitter, long battery lifetime 10 years)

The LoRa community, as open-source, is embracing new developers, and this community is encouraged to use LPWAN technology related to practical IoT applications. This technology is gaining strength in the IoT field because developers share each other's knowledge and experiences.

In this thesis, we have configured the LoRa gateway with TTN server and investigated various characteristics of LoRaWAN like Time on Air (ToA), range, etc. We have also computed the statistical difference between the experimental and the theoretical values for various LoRa configurations, such as SF, coding rate, payload size, etc. Also, this research will serve as a tool to teach, encourage, and share knowledge with students who are pursuing electrical and computing engineering careers to innovate and create new IoT applications.

1.2 Literature Survey

LoRa attracts considerable attention for both academic and industrial purposes. For example, one evaluation report by Andrew Wixted et al. evaluates the physical layer characteristics of LoRa in the central business district of Glasgow - Scotland for both indoor and outdoor locations. The results showed that LoRa technology can be a *reliable link* for IoT applications, reaching outdoor connections up to 2.2 Km and a small residual packet loss of around 1% [19]. Furthermore, LPWAN technology can work with mobile networks, primarily through 4G and 5G [20]. Another study by Alexandru Lavric and Valentin Popa describes the challenges of IoT with emphasis on the LoRa. [21].

A similar study was carried out by Ramon Sanchez-Iborra et al., in Murcia - Spain, where the authors focused on modifying LoRa physical layer parameters such as Spreading Factor, coding rate, and bandwidth, as well as describing the most appropriate LoRa physical layer configuration for each scenario. A CR of 4/8, SF of 7 and byte payload of 20/40 were chosen for various scenarios such as urban, suburban and rural. These scenarios or locations are well defined, such as urban, suburban, and rural [3]. This study concluded that the LoRa wireless link depends on the propagation conditions and highlights the trade-off between link robustness and transmission data rate.

Other studies have demonstrated the need for performing signal coverage simulations for both planning and decision-making. The signal coverage is the principal feature to decide which is the most appropriate technology for one specific application. Raul Parada et al. carried out an experiment in Gran Canaria Island - Spain [22] and proposed the Internet of Things Area Coverage Analyzer (ITHACA) prototype for LPWAN signal coverage maps. On similar lines, Gilles Callebaut et al. evaluated the LoRa coverage path loss for the star-of-stars topology in various environments, such as urban, forest, and coastal [23]. Also, Rida El Chall et al., investigated the LoRaWAN radio channel in the 868 MHz. This work was carried out for both indoor and outdoor locations (urban and rural) in Lebanon (Saint Joseph University of Beirut campus). It was demonstrated that the coverage up to 8 km is obtained in an urban area in contrast to 45 km in rural. They demonstrated the reliability of this technology for LoRa IoT communications [24].

1.3 Description of the Research Project Architecture

The proposed research project develops an end-to-end IoT application that is carried out using LoRa wireless communication from *Sensors* to the cloud via *LoRa gateway*. Therefore, this research work uses the Dragino LoRa IoT Development Kit 915 MHz, with different LoRa wireless sensors such as temperature, humidity, and flame sensor. Additional hardware requirements were: *Field Test Device* LoRaWAN 915MHz ARF8124AA, Dragino LG308 LoRaWAN Gateway, and the 5-way flame sensor module. Subsequently, the gateway sends the sensor's information (via the Internet) to the IoT cloud servers. The IoT cloud platforms or servers are *The Things Network*, *ThingSpeak*, and the integration with *Cayenne my Devices*. The datasheet of these devices is provided in the Appendix. The software requirements were: *Arduino IDE* to program sensors, *Wireshark* to measure the delay of packets, and *CloudRF* to compute the theoretical coverage. The architecture of the project has been divided into three main blocks, LoRa wireless sensors *Block 1*, LoRaWAN Gateways Dragino LG308/LG01-N *Block 2*, and IoT Cloud Platforms *Block 3* (Figure 1.5).

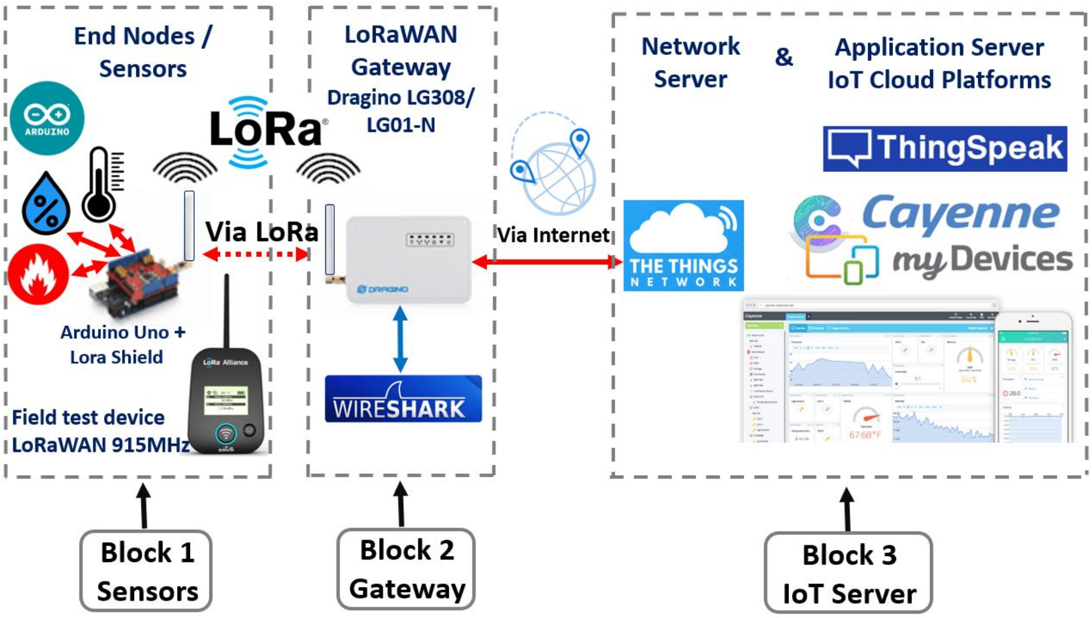


Figure 1.5: Description of the Research Project Architecture

The Dragino LoRa IoT Development Kit 915 MHz includes one indoor gateway LG01-N indoor, two Arduino UNO, one LoRa shield, one LoRa GPS shield; flame sensor; relay; photosensitive sensor; buzzer; ultrasonic sensor; and DHT11 Temperature and Humidity Sensor [25]. Figure. 1.6 displays the kit components.

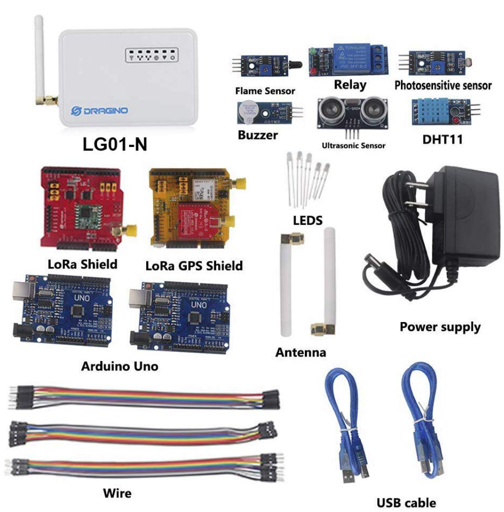


Figure 1.6: Dragino LoRa IoT Development Kit [25]

1.3.1 Block 1 - Sensors - End Nodes

Block 1 presents the specifications of various hardware and software tools required for experimental setup and implementation. Table 1.2 gives a brief description of each component.

Table 1.2: Components of Block 1

Item	Name	Type / Description
1	Arduino IDE	Software to write code and upload it to the Arduino Uno board
2	Hercules Setup	Software to configure the Field Test Device
3	Arduino Uno	Hardware open-source micro-controller board
4	LoRa Shield	Module or transceiver which provides LoRa communications
5	DHT11	Temperature and humidity sensor
6	Flame Sensor	Infrared sensitive to flame wavelengths (760nm to 1100nm), range 60°
7	5 Way Flame S.	5 Way Infrared, detecting range > 120 °
8	Field Test Device	Measures the strength and quality of radio signal

The ***Field Test*** term is typically associated with a device that measures the strength and quality of radio signal; therefore, the Field Test Device LoRaWAN 915MHz ARF8124AA developed by Adeunis RF (Figure 1.7), provides a connection to the LoRaWAN network and allows user to measure and view network coverage data such as ***RSSI*** (Received Signal Strength Indicator), ***SNR***, and ***SF***. It also provides additional information such as GPS coordinates, temperature and battery life [26].

Specifications of Field Test Device (FTD) are presented on Table 1.3.

1.3.2 Block 2 - Gateway

The *LoRa gateway* is a bridge between the wireless sensors and the internet network. The sensors are connected to the gateway via LoRa technology, and the gateway is connected to the cloud platform using the Internet. A prior registration of the gateway to the IoT server platform is re-

Figure 1.7: Field Test Device LoRaWAN 915MHz ARF8124AA

Table 1.3: Specifications of Field Test Device

Parameter	Description
Range	Up to 25 km
Power	Up to 100 mW
Radiated RF power	Up to 20 dBm
Sensitivity	Up to -140 dBm
Frequencies	902-928MHz
Modulation	LoRaTM
Additional Feature	Transmission Button and Accurate GPS

quired before connecting sensors to the internet. Further, an open-source network analysis tool, ‘Wireshark’ software is used to connect to the LAN port of the gateway. It captures network traffic on the gateway and measures the delay in the packets sent by the sensors. Two types of Dragino gateways were used: (1) LG01-N LoRa Gateway and (2) LG308 LoRaWAN Gateway; Table 1.4 presents a feature comparison of these gateways [27].

Table 1.4: Dragino Gateway Feature Comparison

Feature	LG01-N LoRa Gateway	LG308 LoRaWAN Gateway
Dynamic data-rate (DDR)	No	Yes
Sensitivity	-148 dBm	-142.5dBm
Chip Set	SX1276	SX1301 concentrator
Overview	Chip Set Limitation	Standard LoRaWAN device
Description	Single Channel LoRa	10 + 1 Channel LoRaWAN
LoRa module	1 x SX1276	1 x SX1301 + 2 x SX1257
TX/RX Channels	1 x TX or 1 RX , half duplex	10 x RX + 1 TX
LoRa Controller	AR9331 24K MIPS / Linux	AR9331 24K MIPS / Linux
LoRaWAN support	ABP / OTAA Limited LoRaWAN	Standard LoRaWAN
Type of Network Cell	Femotocell	Macrocell/Picocell
Open Source	Yes	Yes

Figure 1.8 shows the Dragino Gateways LG01-N LoRa and LG308 LoRaWAN.

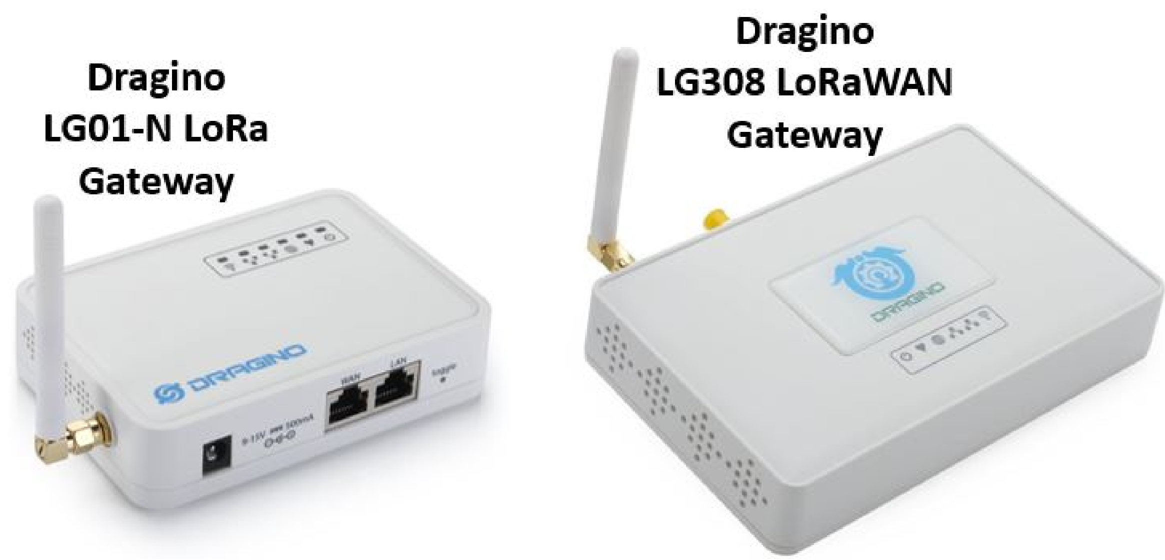


Figure 1.8: Dragino Gateways LG01-N LoRa and LG308 LoRaWAN

1.3.3 Block 3 - IoT Cloud Platforms: Network and Application Servers

Block 3 includes IoT servers i.e., Network and Application servers. A *Network Server* as known as LoRaWAN Network Server (LNS) provides management functions such as authentication of the sensor, security, 128 bits AES connections, message integrity as well as traffic control among wireless sensors and LNS [28]. One example of LNS is The Things Network. The *Application Server* manages the sensors' data (payload), which is interpreted and displayed on the dashboards. Also, the sensors' data can be used for future analysis by users. One example of an Application Server is *Cayenne* from "myDevices" (IoT Solutions company).

Furthermore, these servers include a *Join Server*, which manages two types of activation process: 1. Over the Air Activation (OTAA) and 2. Activation by Personalization (ABP). The activation process is carried out using keys such as: Network Session Key(NwkSKey) and Application Session Key(AppSKey) as well as the End Device Address (DevAddr). These keys must be shared among the sensor and the Join server. Depending on the activation process for each sensor, the Join server may possess the following keys and identifiers (Table 1.5).

Table 1.5: LoRaWAN Keys of Security

Keys and Identifiers	Short Name	bits
Device EUI	Dev-EUI	64
Application EUI	App-EUI	64
App Key	App-Key	128
Device Address	DevAddr	32
Network Session Key	NwkSkey	128
Application Session Key	AppSkey	128

1.4 Thesis Contributions

This thesis evaluates the performance of LoRa technology by carrying out a real-time data transmission between the sensors and the gateway for various ***physical layer*** configurations. The performance analysis is carried out in terms of SNR, packet delay, communication range, etc. for both indoor and outdoor environment. The experimental results were compared with the theoretical values and a 't-test' is performed to determine if there is a significant difference between the statistical values of the observed and theoretical results. Furthermore, the configuration setting of software/hardware is worked out to allow the exchange of the real-time data from the sensors (temperature, humidity and flame sensors) with the two IoT servers: The Things Network and ThingSpeak servers. The thesis contributions are as follows:

1. Indoor Environment Test- **348** configurations (120 among SF, BW, and CR + 228 among SF, BW, CR, and Payload)

   The LoRa communication has different radio configurations such as ***SF***, ***signal BW***, ***coding rate***, ***preamble length***, LoRa sync word, and frequency. Therefore, 120 different configurations are carried out between SF, signal BW, CR, with a fixed payload size at 29 Bytes. Figure 1.9 shows an illustration of variety of these configurations, and Table 1.6 shows the values of each radio parameter.

Table 1.6: Radio Parameter Settings

Radio Parameter	Value
SF	7, 8, 9, 10, 11, 12
CR	4/5, 4/6, 4/7, 4/8
BW (KHz)	10.4, 62.5, 125, 250, 500

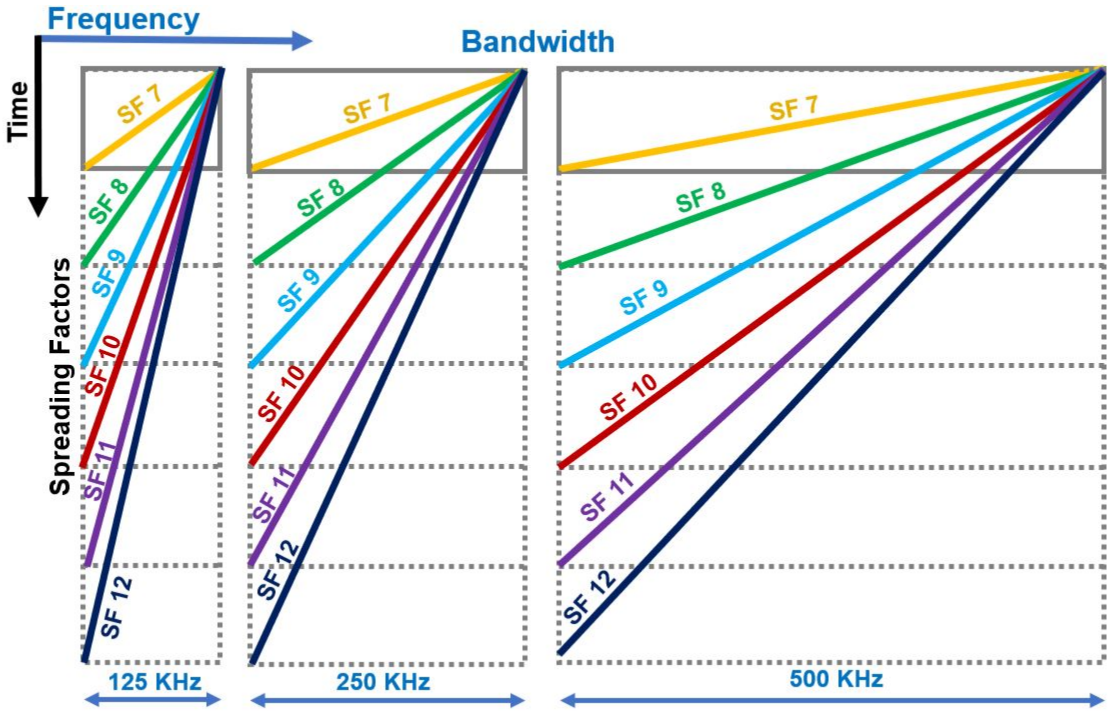


Figure 1.9: Different Settings Between SF and BW

These settings are made on both sides: the sensors and the gateway. On the sensor side, the software Arduino IDE was used to change radio parameters (SF, BW, CR, and Payload), as well as the Serial Monitor tool to visualize the time when the sensor sends the LoRa signal. Simultaneously, the gateway settings are matched with the sensor settings. Also, a connection is established between the gateway and the computer terminal to access the gateway's Linux console. A Wireshark software, which is a sniffer protocol software that is installed on the PC to visualize the time when the gateway receives the LoRa signal into the SSH package (Figure 1.10). When the LoRa signal is sent from the sensor, it takes a certain amount of time to arrive at the gateway. This time is known ***Time on Air or Airtime***. Therefore, the ToA can be computed by subtracting the ***Received time*** from ***Sent time***.

Out of ***120*** configurations, only ***57*** configurations met the FCC requirement of ToA ¡ 400 ms. Therefore, the payload was increased to these 57 configurations from 29 to 51, 62, 84, and 118 Bytes, making ***228*** new configurations. The performance metric, equipments, and softwares are detailed in Table 1.7:

Table 1.7: Equipment used for Indoor Environment Test

Keywords	Description
Sensor	Arduino Uno + LoRa Shield + temperature, humidity, and flame
Gateway	Dragino LG01-N LoRa
Software	Arduino IDE, Putty, Airtime calculator, and Wireshark
Adaptive Data Rate (ADR)	Disable, manually radio settings (SF, BW, and Tx. Power)
Performance metric	Time on Air (ToA) / Airtime [ms]
Comparison	Experimental vs. Theoretical ToA

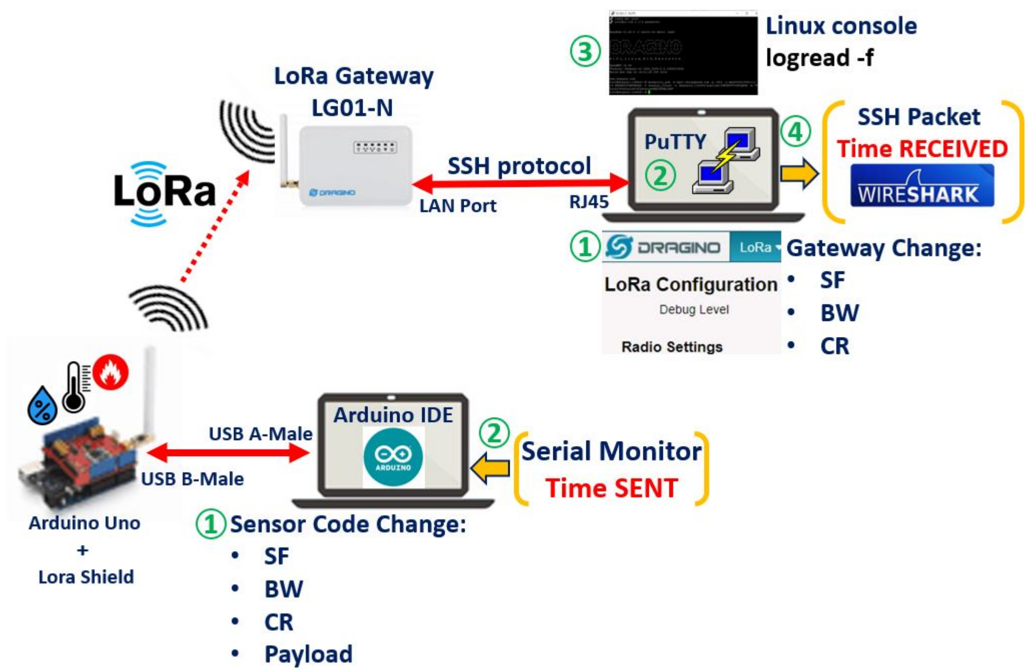


Figure 1.10: Time on Air Measurement Scheme

2. Outdoor Environment Tests - Adaptive Data Rate Feature and Propagation Study The outdoor tests are carried out between FTD (End Node) and Dragino LG308 LoRaWAN gateway. In this case, the ADR is activated to allow the variation of SF with distance. The data is received on TTN which is integrated with Cayenne.

   (a) ADR Feature Link Budget Analysis

Table 1.8: Equipment used for Outdoor Environment Test

Keywords	Description
Sensor	Field Test Device (FTD) LoRaWAN 915MHz ARF8124AA
Gateway	Dragino LG308 LoRaWAN
Software	Arduino IDE, Hercules Setup, Propagation Loss calculator
Adaptive Data Rate (ADR)	Enable
Performance metric	RSSI [dBm], SNR [dB]
Comparison	Experimental vs. Theoretical RSSI [dBm]

When the ADR is activated on FTD, the network automatically adjusts the SF value according to the link distance, and the users can not force a particular value of SF. In contrast, if ADR is deactivated, the user can set up a specific SF value, which is contained in register S201 [29].

(b) Propagation Study

Theoretical coverage simulation is performed using the radio planning tool "Cloud RF" [30], which uses accurate terrain elevation data and propagation models such as Okumura-Hata.

1.5 Thesis Organization

The thesis is organized as follows: Chapter 1 presents the literature survey and motivation for working on LoRa technology. It also summarizes the architecture of the research work which is divided into three blocks:sensors, gateway and IoT servers. Chapter 2 provides a technical overview of LoRa and LoRaWAN, including network fundamentals, modulation, regional parameters, and ADR feature. Chapter 3 describes the methodology and the configuration settings to build an IoT application. Results and discussions for indoor and outdoor environmental tests are presented in Chapter 4. Finally, conclusion and future work is given in Chapter 5.

Chapter 2

LoRa and LoRaWAN Technical Overview

This chapter describes the theoretical principles of operation of LoRa technology focused on the ***physical layer***. Various radio parameters such as ***spreading factor***, ***coding rate***, ***bandwidth***, ***preamble***, etc., as well as the modulation and demodulation process of the LoRa signal is presented in this chapter. Additionally, the Federal Communication Commission (FCC) regulations on the 915 ISM band as the maximum power allowed for down-link, up-link, and ***time on air*** are identified, and the chapter is concluded with the study of the ***adaptive data rate*** feature.

2.1 LoRaWAN Network Fundamentals

LoRaWAN is an open networking protocol and it is standardized and managed by the LoRa Alliance [10]. LoRa is defined within Physical (PHY) layer and LoRaWAN is defined within Medium Access Control (MAC) layer. Therefore, LoRaWAN determines the system architecture, communication protocol, and other services such as interfaces for the upper layers of the network (Figure 2.1).

LoRa is purely PHY layer technology based on a Chirp Spread Spectrum (CSS) *modulation technique*, which is patented by Semtech's technology in order to allow the long-range communication among sensors and gateways. [31]. The Semtech company develops LoRa's chipset or transceivers. For example, the Dragino LG01 gateway uses the SX1276 transceiver [32], and Dragino LG308 uses SX1301 base-band chip, which is a massive digital signal processing, as well as integrates the Lora concentrator IP and dynamic data-rate (DDR) adaptation feature [33].

One important component of the physical layer is the ***spreading factor*** where the original data signal is spread by the amount of SF. The SF configuration has a great impact on coverage range and data rates [10]. LoRa's modulation has spreading factors from SF7 to SF12, where the SF12 is used for farther communication (high gain - amplitude) as it has more time on the air, known as ***airtime*** [28]. In contrast, SF7 (default value) has low gain with high data rate. Furthermore, LoRa presents a reliable connection because it performs error coding (detection and correction) that is defined by ***coding rate***, which can be customized to 4/5, 4/6, 4/7, and 4/8. Finally, the ***bandwidth*** can be set to 125 KHz, 250 KHz, and 500 KHz. These layers can be customized for various settings such as spreading factor, Coding Rate, signal bandwidth, frequency, preamble length, etc.

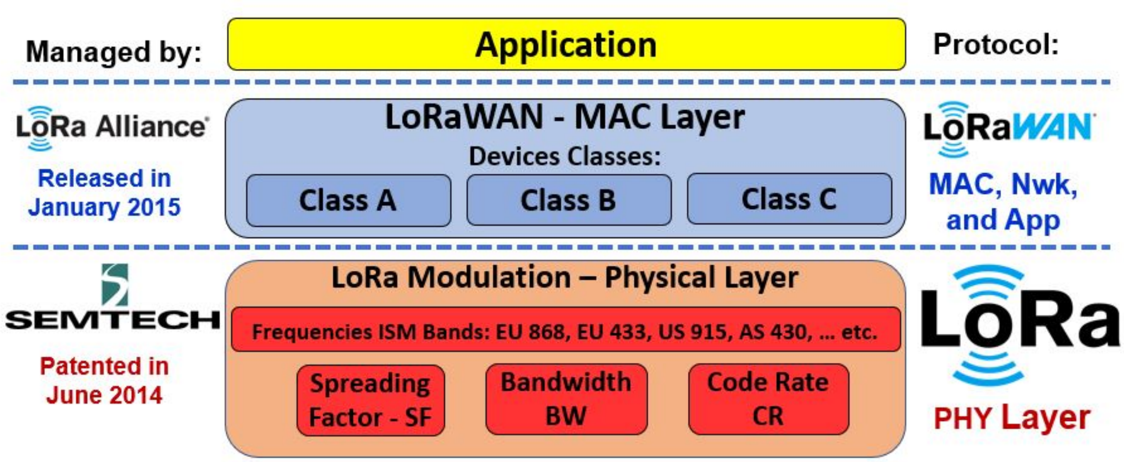


Figure 2.1: LoRa and LoRaWAN Technology Stack

2.1.1 LoRaWAN Network Architecture

A typical topology of a LoRaWAN network includes the following components:

1. ***End Devices or Sensors (S)*** are also known as MoTe (Mobile Termination) or nodes. These devices are built with Semtech's LoRa transceivers, which provide long-range spread spectrum communication.

2. ***Gateways (G)*** are also called as base stations or concentrators. Gateways relay data among end devices (sensors) and a network server.

3. ***Network Server (NS)*** routes the sensors' data to the associated application server that responds back to sensors [34]. It provides authentication to the sensors, manages network security (NwkSkey 128 bits), controls data rates, and eliminates duplicate data [35]. Therefore, the primary responsibility of the NS is battery optimization (controlling power transmission), assuring security, and data routing.

4. ***Application Server (AS) - Console*** contributes to the security (AppSkey 128 bits) of payload and displays the data to the users using a user-friendly interface such as widgets, charts, and dashboards. Figure 2.2 presents the typical LoRaWAN architecture.

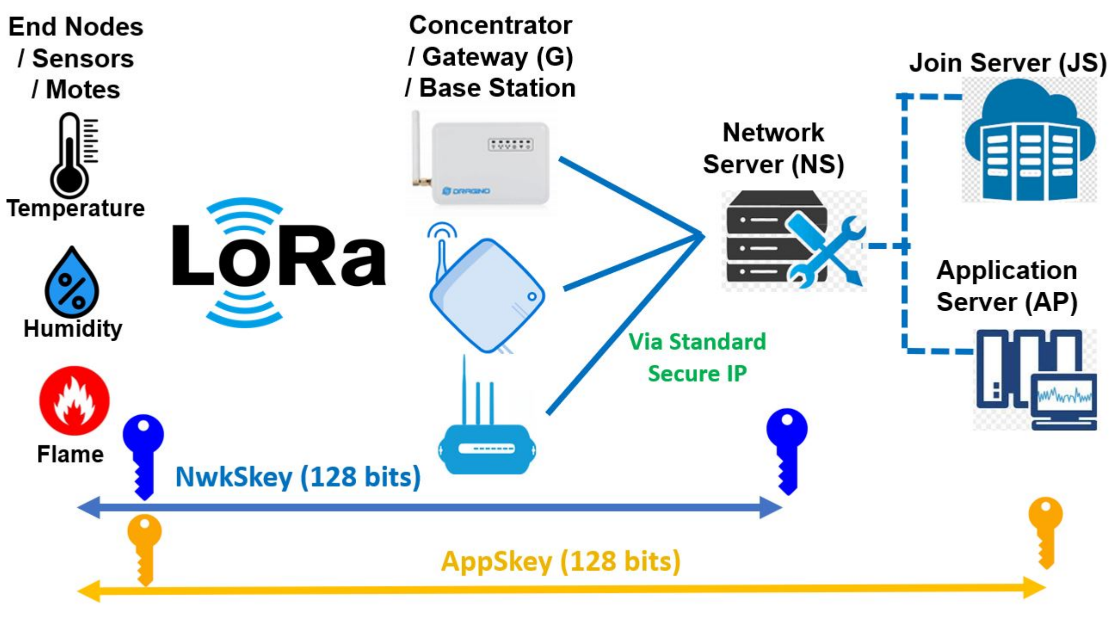


Figure 2.2: LoRaWAN Architecture

2.2 LoRa Modulation and Demodulation

Theoretically, modulation is the process of changing the parameters of the carrier signal in accordance with the instantaneous value of the modulating signal (information carrying digital or analog signal). Modulation types used for analog signals are: Amplitude Modulation (AM), Frequency Modulation (FM), Phase Modulation (PM), and some combination of the above. Similarly, digital signal modulation could be used: Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). LoRa technology applies the concept of FSK [36], where binary bit **"1"** is represented one frequency ad bit **"0"** is represented by another frequency as shown in Figure 2.3.

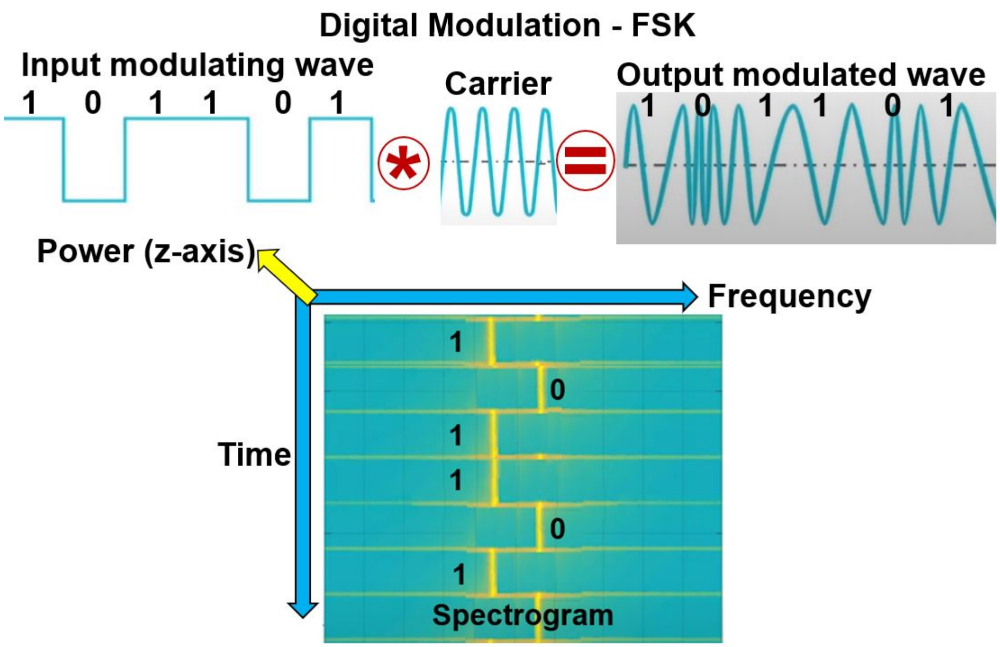


Figure 2.3: FSK Modulation

LoRa physical layer uses Spread Spectrum Modulation technique, which is based on *Chirp Spread Sprectrum modulation*. The spread spectrum technique is a proprietary modulation technique provided by Semtech. The use of CSS enables the transmission of different data rates without any interference. It uses wideband linear (on specific ***Bandwidth***) frequency modulated ***Chirp*** pulses to encode data. In simple words, the CSS technique is procedures in which the signal is spread into the frequency domain. Chirp is also known as ***sweep signal or sweep Rate***, which defines the tone in which the frequency changes with time. There are two types of chirps: ***up chirp*** (for increasing frequency) and ***down chirp*** (for decreasing frequency) as shown in Figure 2.4). For example, the chirps technique is used on marine and military radars, as well as the open-source GNU Chirp Sounder [1]. The bandwidth values specified for LoRa in US is 125kHz, 250 KHz and 500 KHz. It is more restrictive in Europe to just 125 KHz and 250 KHz. Figure 2.5 shows an illustration of the sweep signal length for different configuration of BWs (125, 250, 500 KHz) and SFs (from 7 to 12).

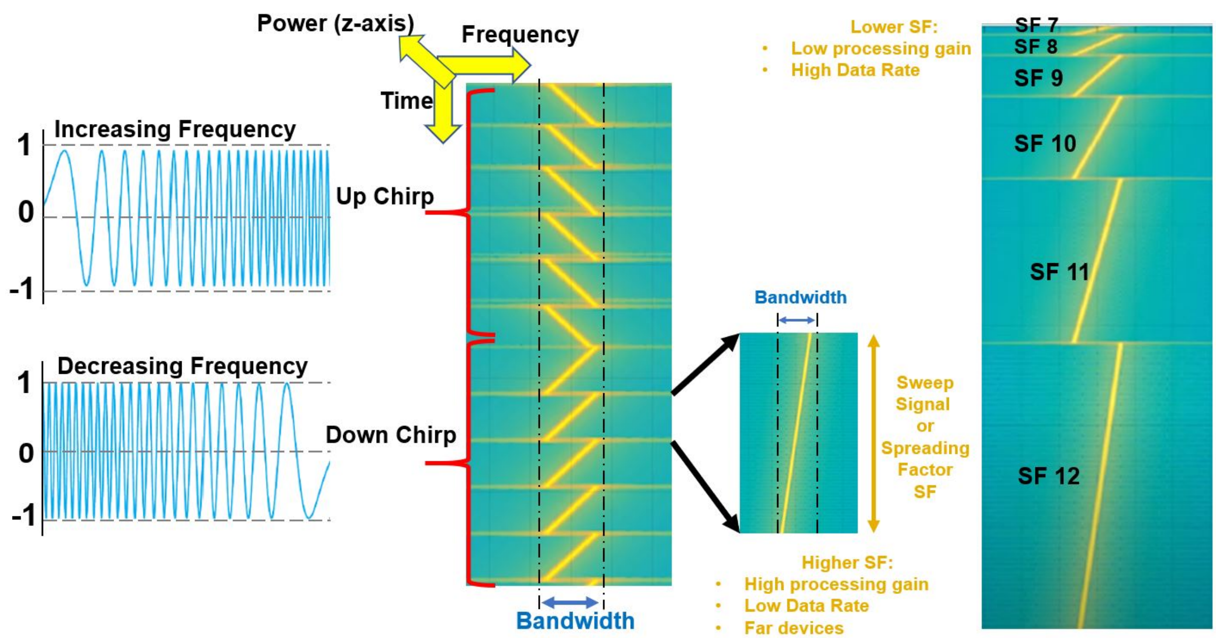


Figure 2.4: Up Chirp and Down Chirp [36]

CSS modulation provides the following advantages [37]:

- Greater link budget
- Resilience to interference
- Performance at low power communication link
- Resistant to multi-path and fading (combined direct and reflected signals)

[1]Software determined radio based receiver for monitoring ionospheric sounders

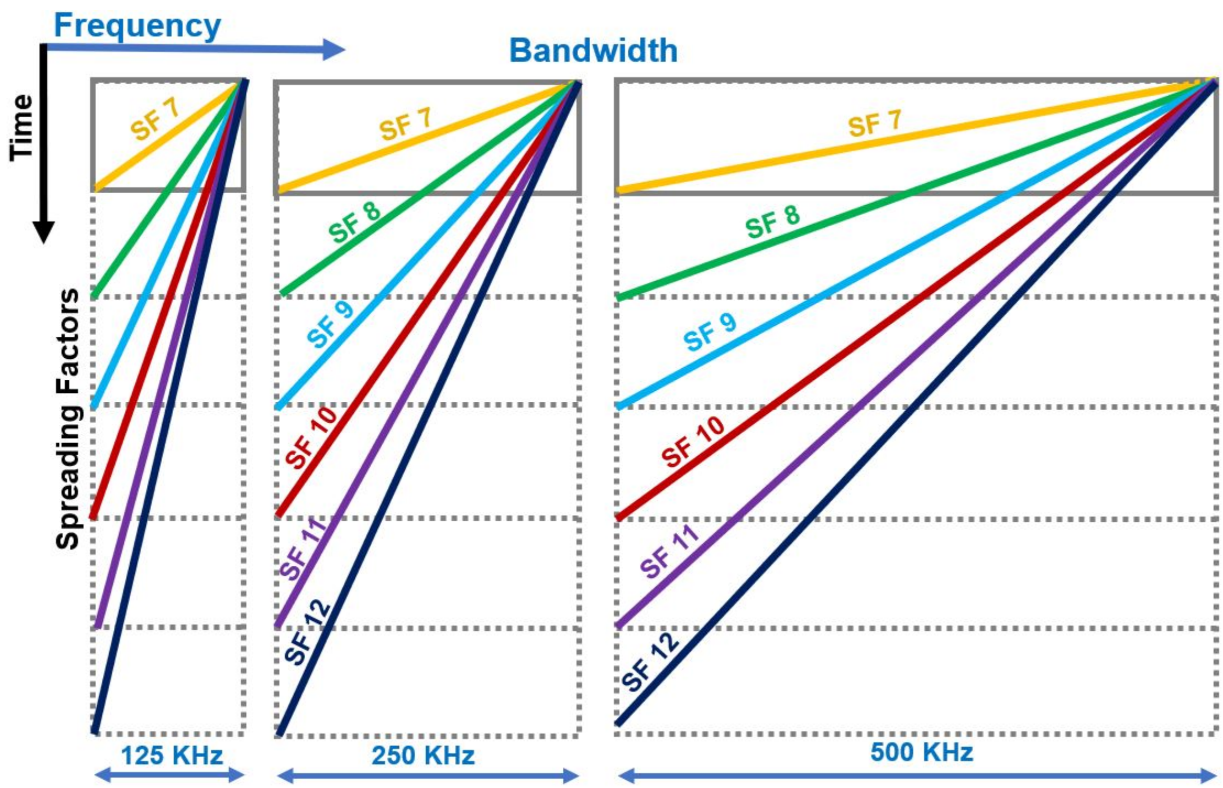


Figure 2.5: Illustration of the Sweep Signal Length

- Doppler effect (for motion sensor applications)
- High receiver sensitivity

Keywords are being defined in Table 2.1.

Table 2.1: Definitions

Keyword	Definition
Symbol	Discrete RF energy state to represent quantity of data (one or more bits)
Possible Symbols	2^{SF} values. One value is encoded into a Up Chirp (sweep signal)
Example	2^7= 128 values (1 bit has two states "0" or "1", SF = 7)
Data Encoding	Symbols represent encoded data. Data is transformed before TX.
Bandwidth	Width of radio spectrum occupied by chirp into the frequency domain
Spreading Factor	Quantity of bits encoded per symbol; US: 7 to 12

The physical frame of LoRa consists of preamble, synchronization bits and the payload. Eight up chirps indicate the start of transmission called the preamble, followed by two down chirps called the synchronizing symbols. Any LoRa gateway can recognize this preamble as the beginning of the packet transmission, which alerts its attention. Actual data transmission begins after the synchronization symbols [37]. The data is encoded into the chirps that jump around the bandwidth arbitrary, or in other words, the data utilizes the chirp spread spectrum technology for transmission. This illustration is shown in Figure 2.6.

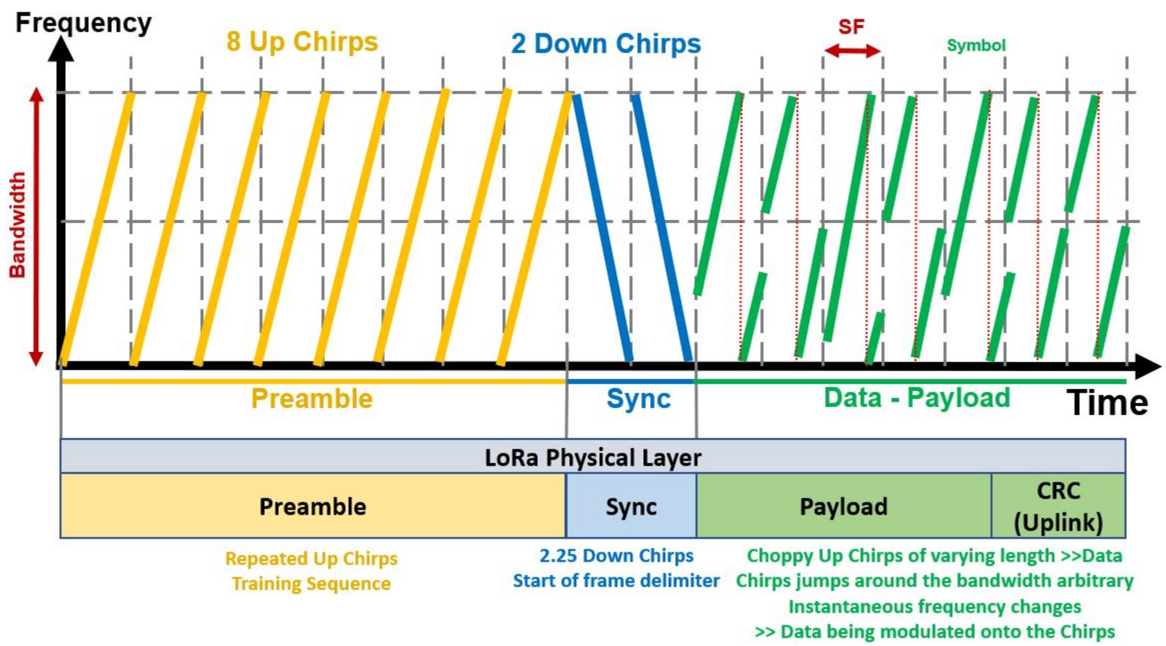


Figure 2.6: LoRa Physical Frame

The lowest SF= 7 means a highest data rate because more chirps are sent per second; therefore, the system can encode more data per second. However, the signal can propagate to shorter distances as the energy of the signal is low. Contrarily, higher SF (12) implies fewer chirps per second, which means fewer data to encode per second. In this case, the signal can propagate to longer distances due to increase in time-on-air (Figure 2.7). This results in better sensitivity, therefore, better sensitivity means longer coverage; therefore, the sensor can receive the signal further away. Each steps up in SF approximately increases 2.5 dB on the link budget [38], according to Eq. 1.2 with Table 1.1.

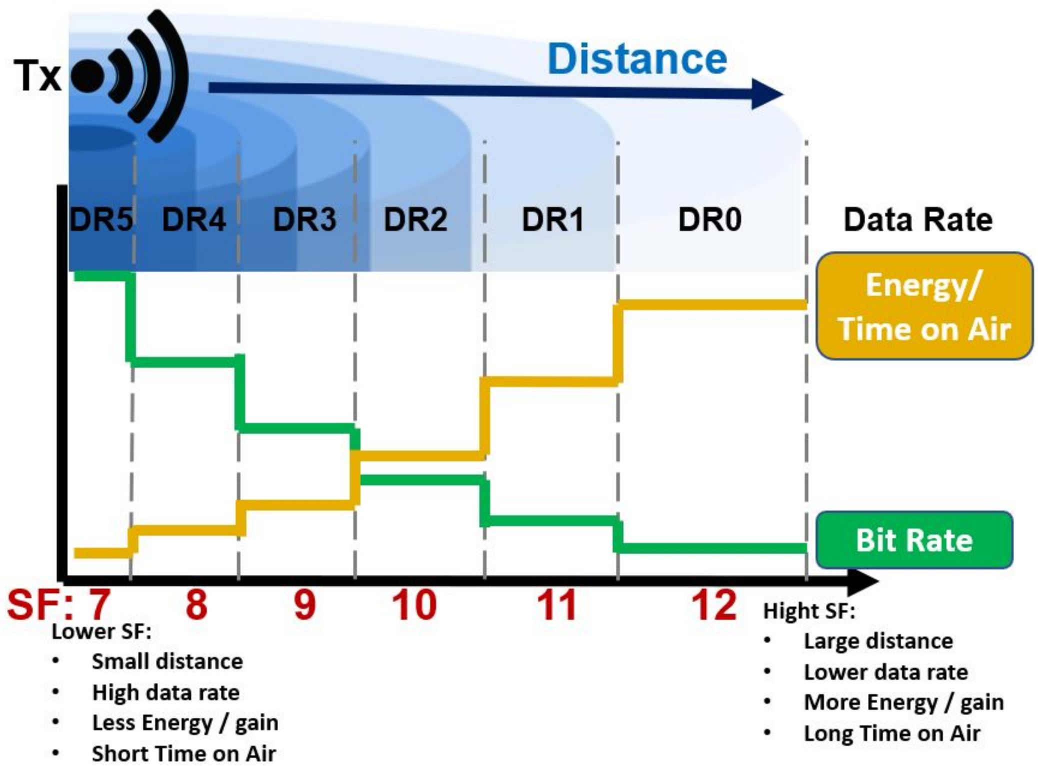


Figure 2.7: Energy vs. Bit Rate [38]

LoRa ***demodulator*** accepts the received signal, ***de-chirps*** it in order to recover the original transmitted signal. It tries to quantify the location where the chirps were jumped. The first step in this process is to extract the data from the LoRa packet and perform de-chirping on it, identifying the preamble, synchronization, and payload data.

The demodulator generates Up chirps and Down chirps at the appropriate SF and BW. For example, the original signal (fo) is multiplied by their complex conjugate (-fo); therefore, the resulting signal is "0" (fo * -fo = 0), which means a constant value. Thus, the LoRa's signal is separately multiplied by Up chirps and Down chirps (appropriate SF). In other words, the received LoRa signal is multiplied by Inverse chirp, resulting in the de-chirp signal. Afterward, the ***Fast Fourier Transform (FFT)*** is taken from the de-chirp signal, where the length of FFT is equal to the number of possible symbols [37]. Therefore, the most intense energy or powerful component in each FFT is the desired symbol. Figure 2.8 [37] illustrates the modulation process.

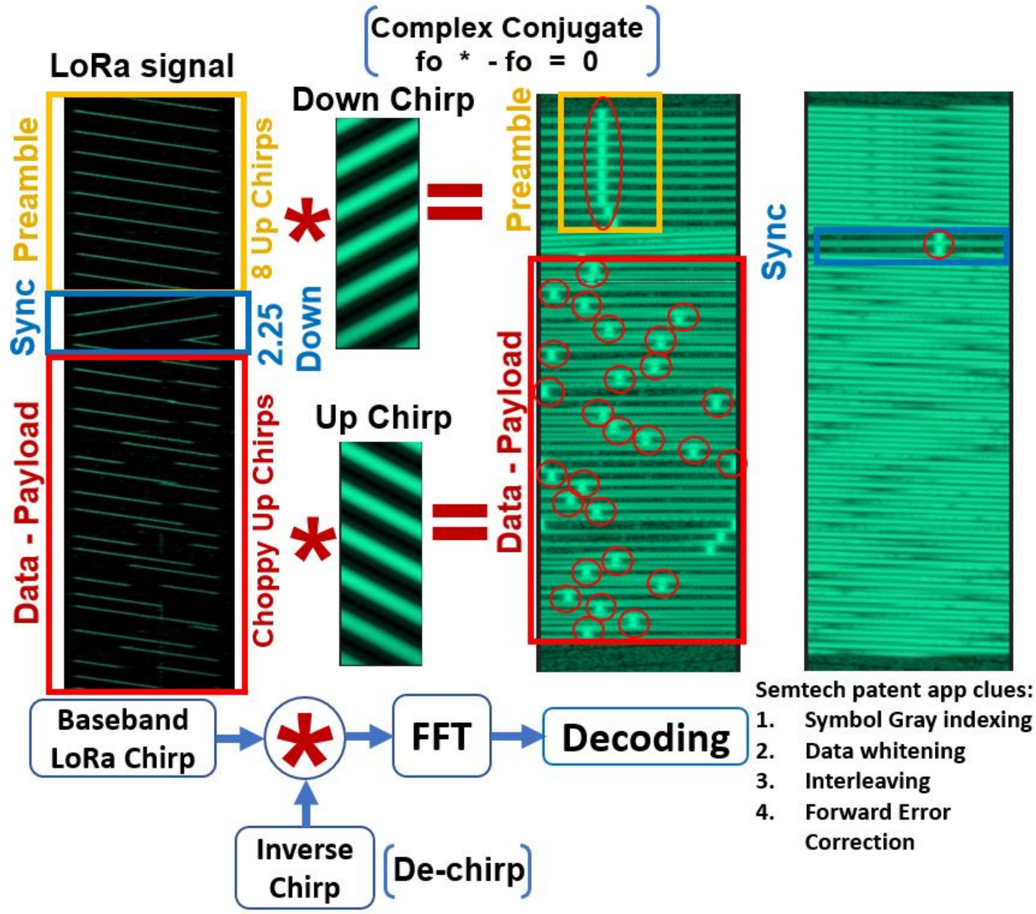


Figure 2.8: LoRa Demodulating [37]

2.3 LoRaWAN Regional Parameters

International organizations handle the spectrum to ensure the interoperability of various radio technologies. Also, the local Telecom agency in each country could add additional rules and parameters. For instance, in Europe, this organization is called the European Telecommunications Standards Institute (ETSI) which defines the maximum transmission power for uplink as 25 mW (14 dBm) and for downlink as 0.5 W (27 dBm) [39]. In all 50 states, the District of Columbia and the U.S. territories have the ***Federal Communications Commission***, which regulates interstate and international radio communication such as television, wire, satellite, and cable. Generally speaking, FCC has one responsibility to process applications and deliver the permit to operate called *License* on a specific frequency and technology [40].

The USA follows the entire FCC Part 15 regulations for the 902 - 928 MHz ISM band, which is known as the 915 MHz ISM Band . The frequency plan is detailed in Table 2.2 and Figure 2.9 [41]. Channel eight (8) is used in this thesis in which it represents up-link channel at 903.9 MHz

Table 2.2: US 902-928 MHz Frequencies Plan

Description	Upstream – 64	Upstream – 8	Downstream – 8
Channels numbered	0 to 63	64 to 71	0 to 7
Number of channels	64	8	8
Frequency starting at	902.3 MHz	903.0 MHz	923.3 MHz
Linearly increment	200 kHz	1.6 MHz	600 kHz
Frequency ending at	914.9 MHz	914.2 MHz	927.5 MHz
Bandwidth	125 kHz	500 kHz	500 kHz
SF varying	SF7 - SF10	SF8	SF7 - SF12
Coding rate	4/5	4/5 - 4/8	4/5 - 4/8

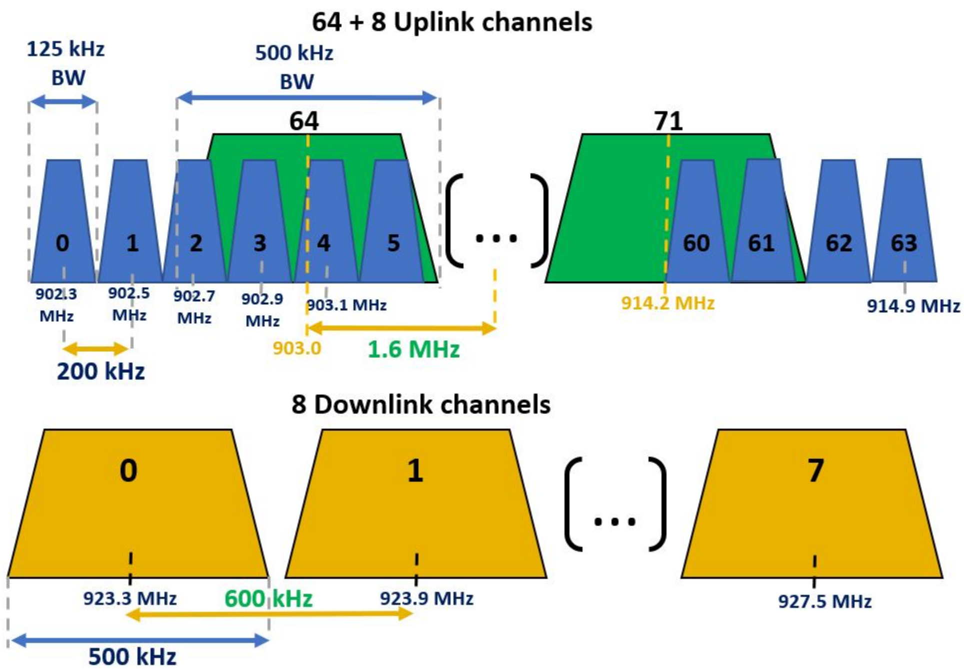


Figure 2.9: US 902-928 MHz Frequencies Up-link and Down-link

The end-devices are demanded to operate under regulatory specifications for the 915 MHz ISM band by FCC. Table 2.3 shows a succinct description of the principal regulations on the 915 MHz ISM bands, as well as Table 2.4 presents characteristics for LoRaWAN on US 902-928 MHz frequencies [28].

Table 2.3: LoRaWAN Regulation for North America

Description	LoRaWAN specification for North America
Frequency Band	902 - 928 MHz
Max. Tx Power Up-link	(30 dBm allowed) 20 dBm is typical
Max. Tx Power Down-link	27dBm
Max. dwell time	400 milliseconds on Up-Links

Table 2.4: US 902-928 Channel LoRa Characteristics

Data Rate (DR)	Spreading Factor (SF)	Bandwidth (KHz)	Up-link or Down-link	PHY Bit Rate (bits/sec)	Maximum MAC Payload (Bytes)
0	SF 10	125	Up-link	980	11
1	SF 9	125	Up-link	1,760	53
2	SF 8	125	Up-link	3,125	125
3	SF 7	125	Up-link	5,470	242
4	SF 8	500	Up-link	12,500	242
5 - 7	Not defined				
8	SF 12	500	Down-link	980	53
9	SF 11	500	Down-link	1,760	129
10	SF 10	500	Down-link	3,125	242
11	SF 9	500	Down-link	5,470	242
12	SF 8	500	Down-link	12,500	242
13	SF 7	500	Down-link	21,900	242

2.4 LoRa Adaptive Data Rate (ADR)

LoRaWAN has an essential feature to adapt the data rate in order to optimize the transmission power (minimize the battery usage) and maximize the data throughput based on radio conditions. These radio conditions are ***RSSI*** in dBm and ***SNR*** in dB. When ADR is enabled, the NS will optimize the transmission parameters to perform the fastest possible data rate. Therefore, the ADR algorithm inputs are the *Link margin* and *SNR* to manage the data rate and transmission power from the sensor to the gateway.

ADR's mechanism uses the following criteria to change the data rate [42]: **1.** It computes the link margin of the system which is the result of subtracting the Rx Power (RSSI) from Rx Sensitivity (presented on Figure 1.3). **2.** Based on the computed link margin and SNR, the data rate can be increased of decreased. The LoRa signal requires a certain SNR value to stay on a specific SF. The needed SNR value and link margin calculations is performed in Table 2.5 [13] assuming the Rx. power as -100 dBm and Tx. power as 20 dBm.

- The data rate could be increased when the link margin is high
  For example, from SF12 $\Rightarrow$ to SF7 (Higher data rate)

- The data rate could be decreased when the link margin is low
  For example, from SF7 $\Rightarrow$ to SF12 (Lower data rate)

Table 2.5: Example Link Margin Calculation

DR	SF	Required SNR dB	Rx Sensitivity dBm	Link Margin dBm
DR5	SF7	-7.5	-125	25
DR4	SF8	-10	-127	27
DR3	SF9	-12.5	-130	30
DR2	SF10	-15	-132	32
DR1	SF11	-17.5	-135	35
DR0	SF12	-20	-137	37

The process begins when the sensor sends the ADR command into the message through the gateway, which forwards the message to NS. LoRaWAN gateway converts the LoRa packets into regular IP packets, which travels into the IP network reaching the Network Server (NS). Therefore, the NS manages the sensors' Up-link transmission parameters such as SF, BW, and Tx. power.

These parameters together plus ***coding Rate*** are used to compute the Data Rate (DR) also known as LoRa modulation bit rate R_b and is given in Eq. 2.1. Furthermore, the NS gathers the last 20 up-link messages and extracts information such as RSSI, DR, and Signal to Noise Ratio from the sensor.

The NS takes the maximum SNR value among the last 20 up-link messages received that is known SNR measured. In the same way, the NS computes the SNR margin using Eq. 2.2. Consequently, based on radio condition, the NS determines the appropriate data rate that the sensor needs to use. Thus the throughput is optimized by varying the SF and BW, as well as saving battery consumption by decreasing the transmission power of the sensor.

$$R_b = SF * \frac{BW}{2^{SF}} * CR \tag{2.1}$$

$$SNR_{margin} = SNR_{measured} - SNR_{required} - Margin_{default} \tag{2.2}$$

The ***adaptive data rate*** feature is developed into the MAC layer through the appropriate MAC commands. If the ADR flag is not enabled, the NS will not try to change the sensor's data rate regardless of the received SNR measurement. The ADR process uses four communication commands between sensor and gateway [43] (Figure 2.10). Commands are described in Table 2.6.

Table 2.6: Adaptive Data Rate MAC Commands

Command	Transmitted by	Description
ADR	Sensor	ADR=0 NS will not control the sensor DR
	Sensor	ADR=1 NS will control the sensor DR
ADRACKReq	Sensor	ADRACKReq=0 NS needs to confirm receipt of msg
	Sensor	ADRACKReq=1 NS doesn't need to confirm receipt of msg
LinkADRReq	NS	Request to change its transmit parameters
LinkADRAns	Sensor	LinkADRAns=0 ACK status rejection final settings
	Senser	LinkADRAns=1 ACK status acceptance final settings

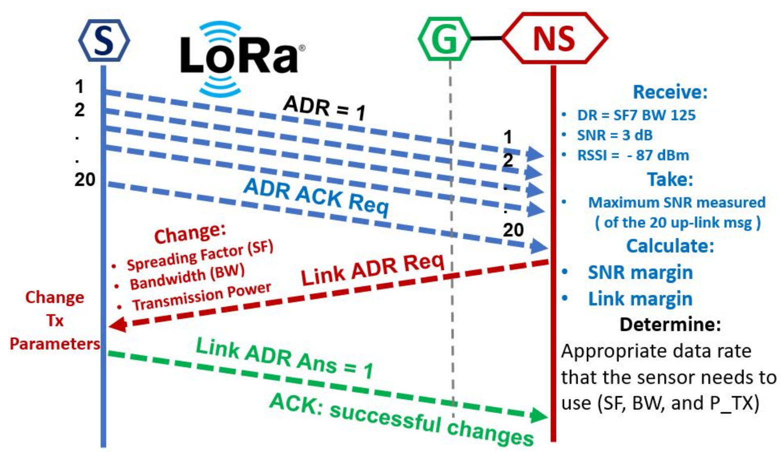


Figure 2.10: ADR Procedure Command Flow

The ADR process can be started from either the NS or sensor. For example, one sensor is connected to the LoRaWAN network and has sent the command ADR=1, which means the NS will control the sensor data rate. By default, the sensor sends the up-link message at the lowest data rate (SF 12). After the up-link message arrives at NS, it analyzes the radio conditions and computes both the link budget and the highest data rate, which could be processed.

In the next step, the NS sends the command LinkADRReq requesting to change its transmit parameters to SF7. The sensor confirms the new SF via LinkADRAns=1, and all future up-links messages are configured at SF7. The sensor periodically sends up-link messages, and also the ADR acknowledge counter (ADR ACK CNT) is incremented. These counter could be incremented until it reaches a predefined limit "ADR acknowledgment limit (ADR ACK LIMIT)". After the sensor reaches the limit, it sends the ADR ACK Req command; similarly, the "ADR acknowledge delay" is predefined by the sensor. Meantime the sensor waits for the NS to respond to the ADR ACK Req. If the sensor doesn't receive NS's response when the "ADR acknowledge delay" has expired, the sensor automatically decreases the data rate one step, which means it changes from SF7 to SF8. At his point, the sensor continues sending up-link messages to the NS at SF8. If the sensor still doesn't receive NS's response, the sensor again decreases the data rate one more step until it reaches SF12 [44] (Figure 2.11).

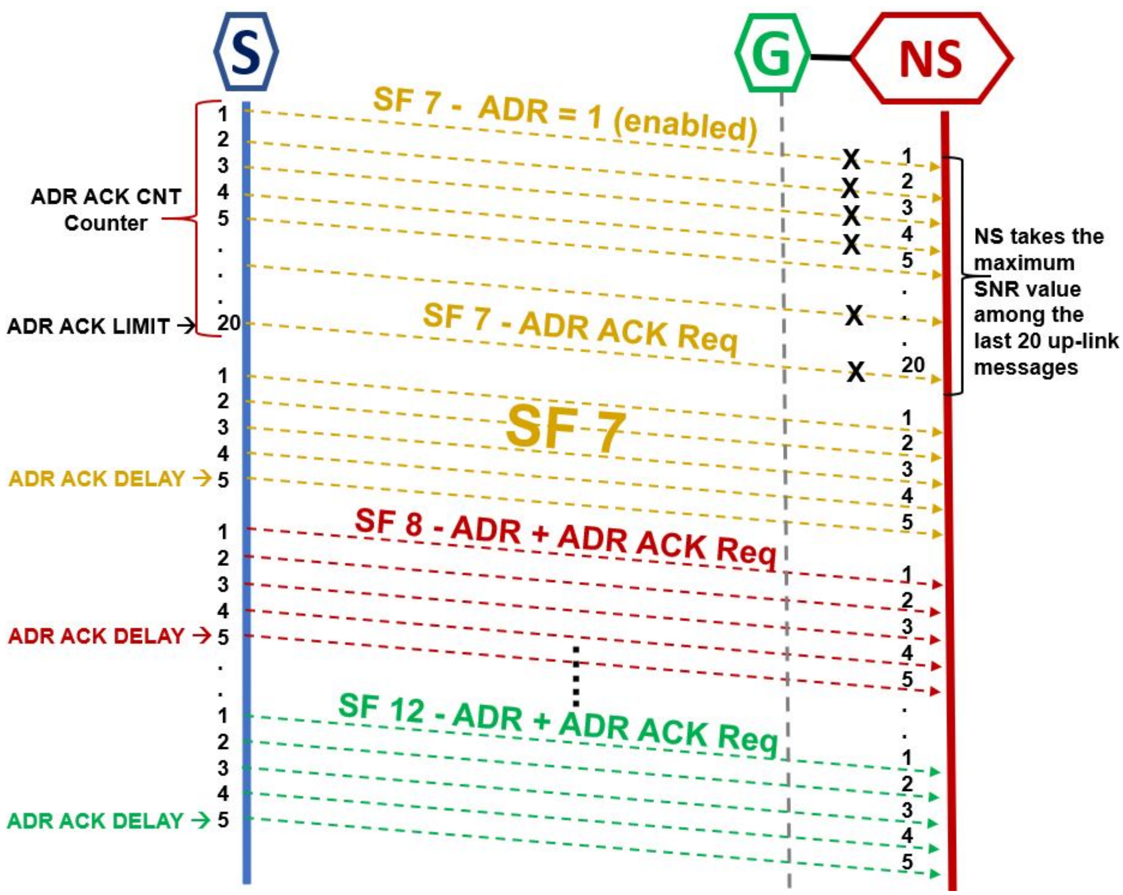


Figure 2.11: Sensor ADR Procedure [44]

Chapter 3
Methodology and Equipment Configuration

This chapter details the methodology and procedures for conducting various sets of experiments. Additionally, all the necessary configurations are detailed to develop an IoT application for two different IoT servers using temperature, humidity, and flame sensors. The first application is made to the IoT server ***"The Things Network"*** with the integration of the application server (AS) ***"Cayenne"***, and the second is the ***"Thingspeak"*** server. In addition, it indicates all the steps to configure the ***"Field Test Device"*** towards The Things Network server, in which FTD is used to measure the RSSI and SNR of LoRa signal. All of these configurations are made for both hardware and software. It is necessary to configure all components such as the gateway, server, and sensors by C ++ codes.

3.1 IoT Application on The Things Network Server Integrated with Cayenne

The first Internet of Thing application is carried out using the Dragino LG01-N LoRa gateway, which forwards the sensors' messages to ***"The Things Network"*** server. This IoT application uses different sensors such as temperature, humidity, and a flame sensor, which are connected on the LoRa shield onto the Arduino Uno board. The Things Network has additional integrations, which is the link to connect sensors to an application server. One integration is ***"myDevices Cayenne"*** which allows visualization of real-time and historical data send over TTN. Additionally, the ***Field Test Device*** (ARF8124AA) was connected to the Cayenne application server. The FTD cannot work with Dragino LG01-N LoRa gateway; therefore, the Dragino LG308 LoRaWAN gateway has been used instead of LG01-N. On the other hand, the Arduino IDE software is used to program the Arduino Uno board. The Arduino code uses the ***LMIC*** library, which allows communication among sensors and LoRa gateway. Furthermore, the software ***Wireshark*** (Sniffer Network Protocol Analyzer) is connected to the gateway to measure packets' delay from sensors. The architecture of this IoT application is shown in Figure 3.1.

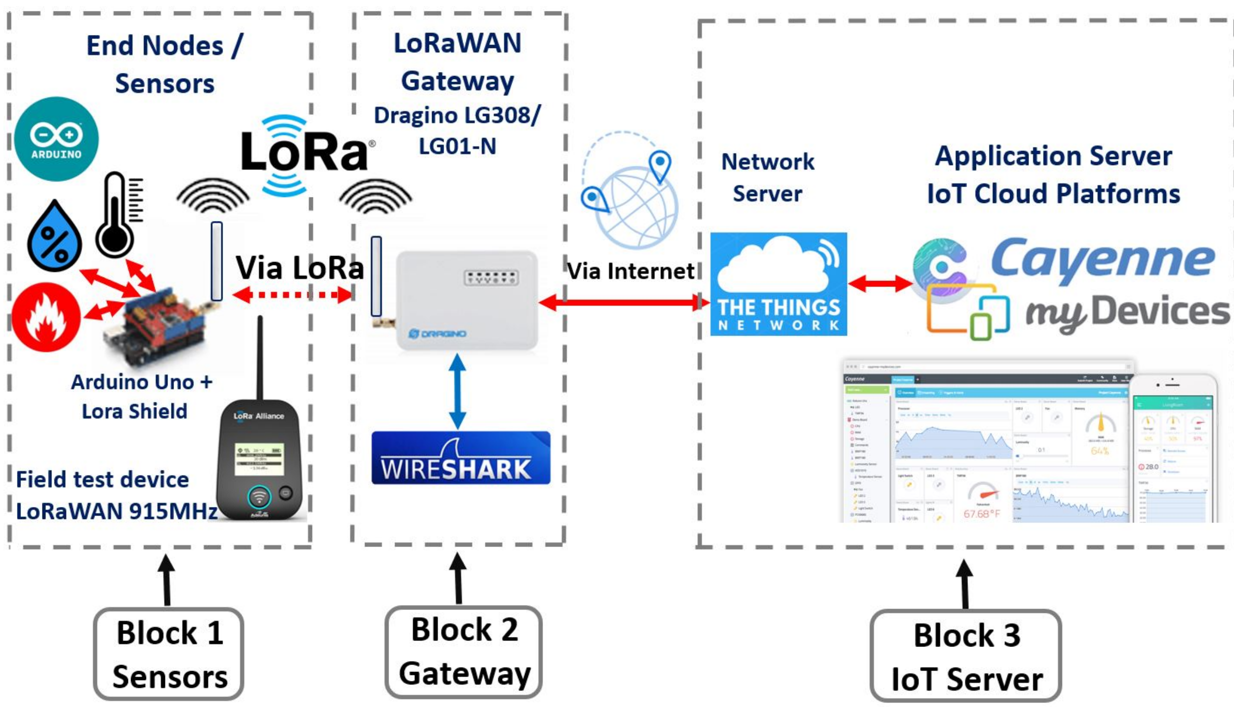


Figure 3.1: Architecture of IoT Application on TTN Server Integrated with Cayenne

3.1.1 Hardware - Gateway Configuration on TTN Server

The LoRaWAN server settings can be found in the ***Service*** menu, followed by the ***LoRaWAN gateway*** option (Figure 3.2). The LoRaWAN settings are shown in Table 3.1.

Table 3.1: Gateway Configuration on TTN Server

IoT Service	LoRaWAN/RAW forwarder
Debug Level	Little message output
Service Provider	The Things Network
Server Address	ttn-router-us-west
Radio Power (Unit:dBm)	20
Frequency (Unit: Hz)	903900000
Spreading Factor	SF7
Coding Rate	4/5
Signal Bandwidth	125 KHz
Preamble Length	8
LoRa Sync Word	52

Every LoRa gateway has a unique ***Gateway ID*** that is needed to register on the TTN server.

3.1.2 TTN IoT Server Configuration

The first step is to create an account on ***The Things Network*** website (*www.thethingsnetwork.org/*) and sign-in; second, the ***Console*** menu shows two main options to register: 1. ***Gateways***, and 2. ***Applications***. In the Gateways option, chooses "register gateway" and fill out the following information (Figure 3.3). After creating the gateway, the status indicates ***"connected"***.

1. Gateway EUI: A8 40 41 1C F8 E8 12 34 (from Gateway LoRaWAN Server Settings)

2. Select: "I'm using the legacy packet forwarder"

3. Description: UNF Lab (Example)

4. Frequency Plan: United States 915MHz

5. Router: ttn-router-us-west (from Gateway LoRaWAN Server Settings)

6. Location: The location of the gateway is established by clicking on the map

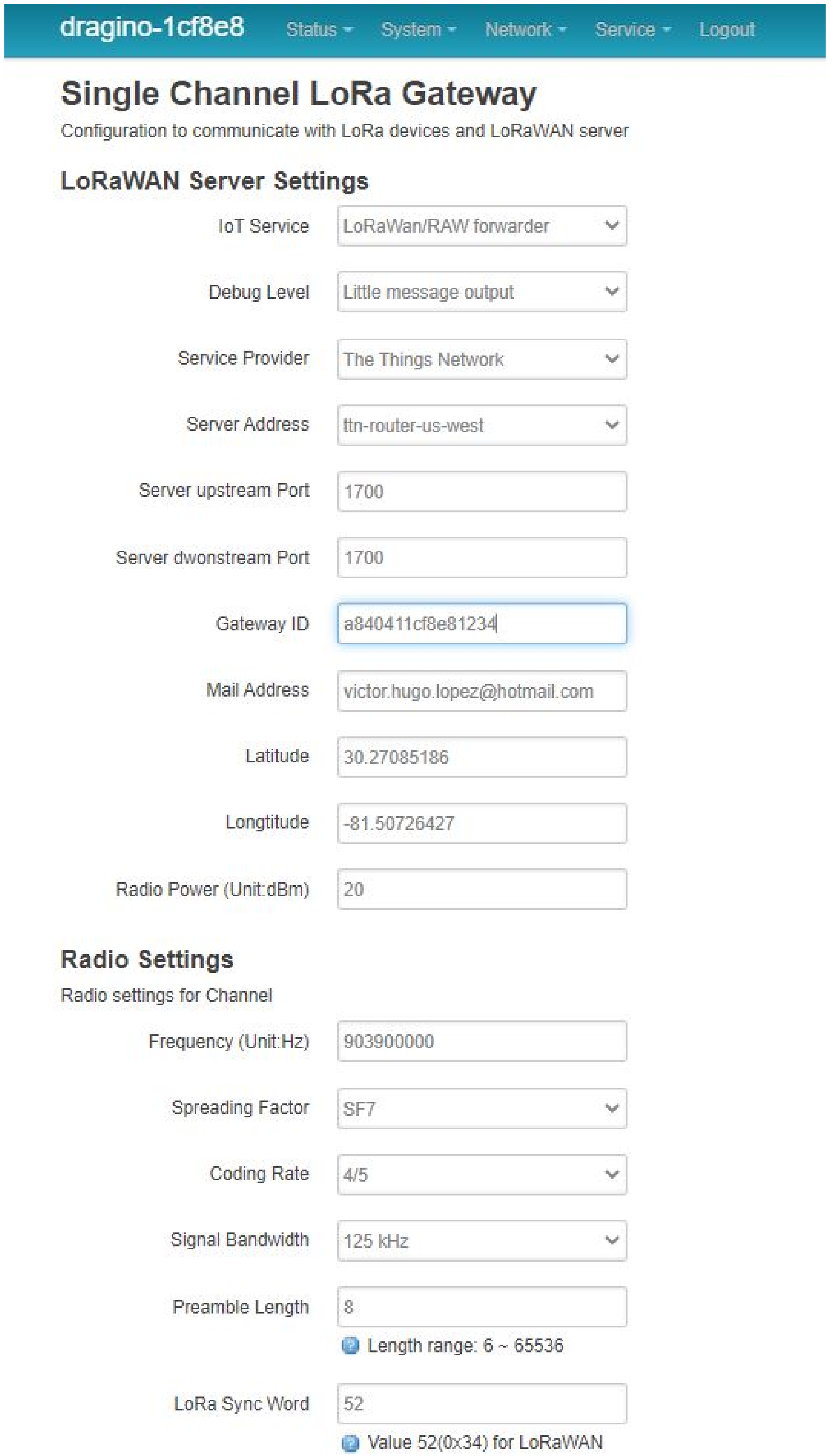


Figure 3.2: Dragino LG01-N LoRa Gateway Configuration on TTN Server

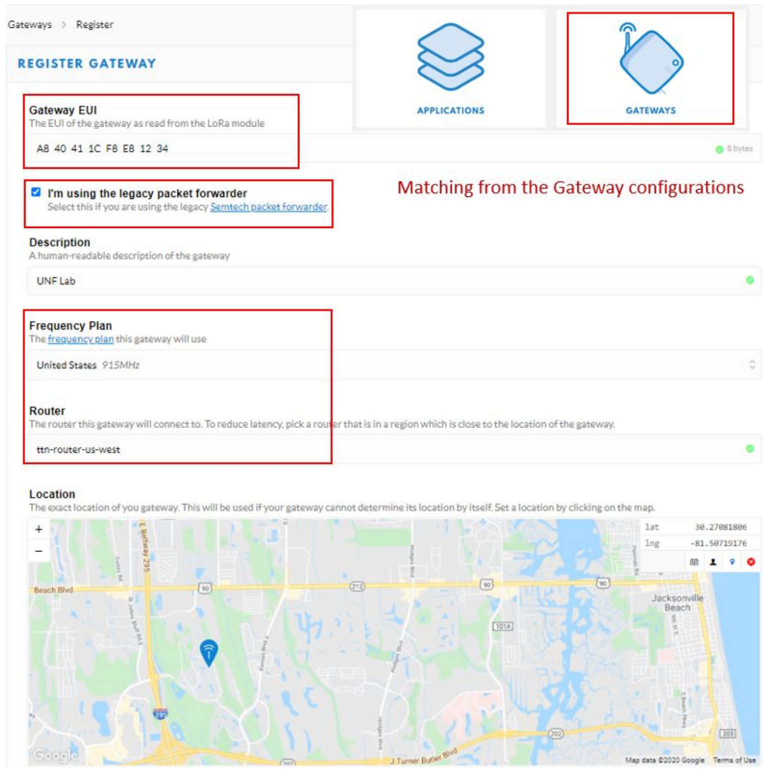


Figure 3.3: Register Gateway Information on TTN Server

The next step is to create an application followed by the device registration (Figure 3.4). An identifier is created to the sensor called ***Device ID*** (Figure 3.5).

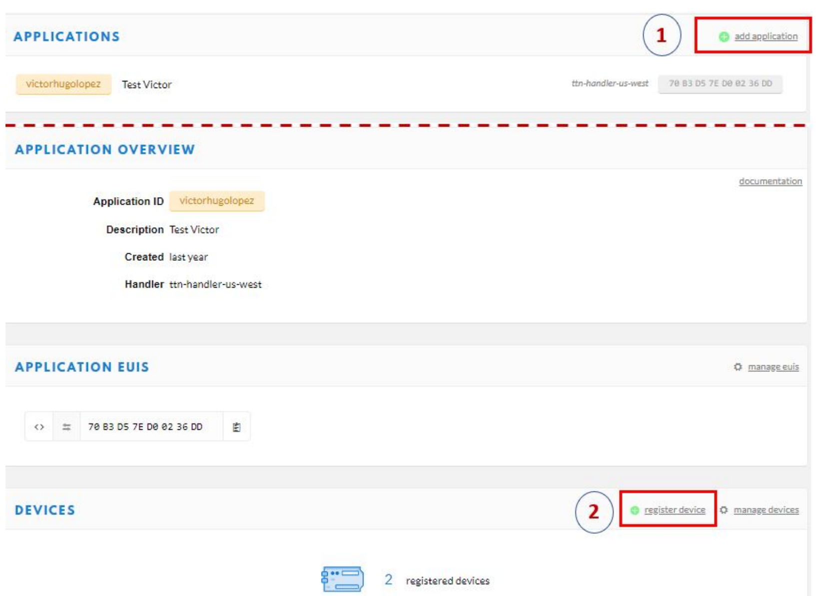


Figure 3.4: Application and Device Registration on TTN Server

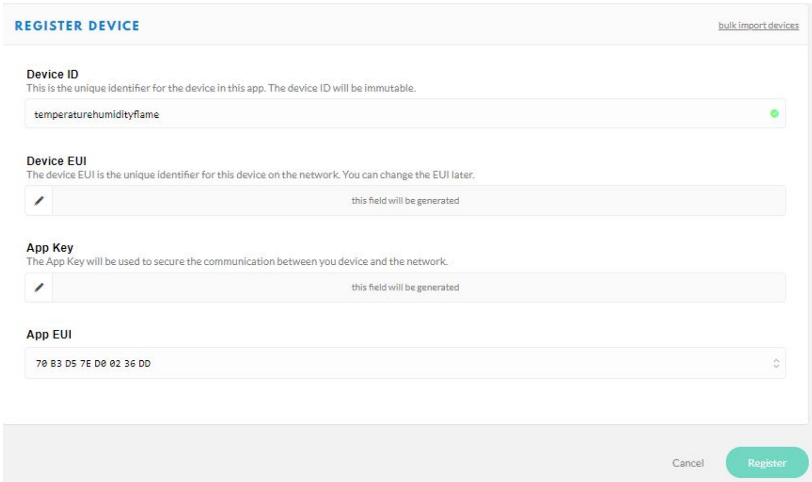


Figure 3.5: Register Device on TTN Server

Also, TTN includes a join server (JS) that manages two types of activation processes or activation methods: ***1. Over the Air Activation (OTAA)*** and ***2. Activation by Personalization (ABP)***. Choosing ABP activation Method under Device Settings, TTN generates Device Address, Network Session Key, and App Session Key (Figure 3.6).

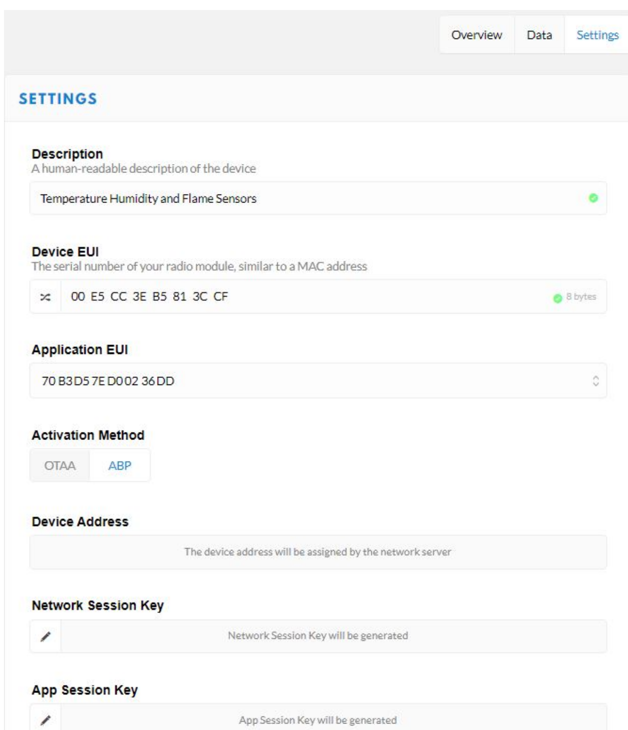


Figure 3.6: Device Settings

These three settings are Network Session Key, App Session Key, and Device Address which are needed to program the sensor (Figure 3.7). At this point, it is necessary to change the activation method from ABP to *OTAA*. Also, into the ***Devices*** menu, select ***Payload Formats*** and choose *Cayenne LPP (Low Power Payload)* (Figure 3.8), finally TTN is ready to receive data from ***"sensors"***.

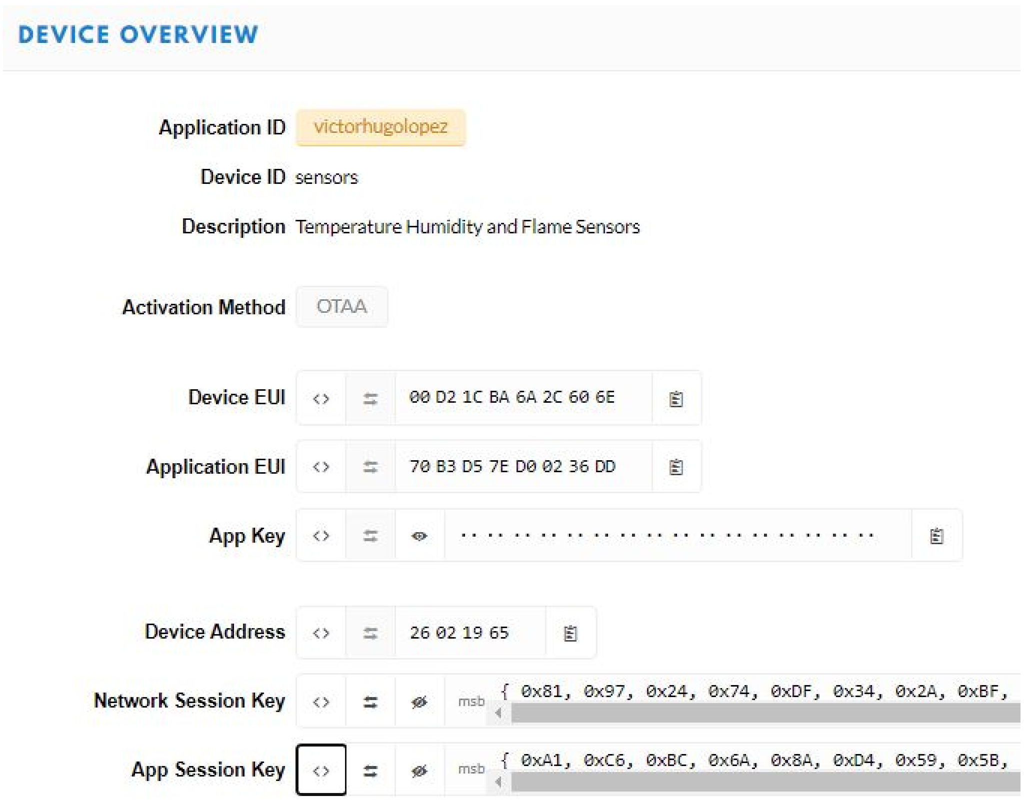


Figure 3.7: Device Overview

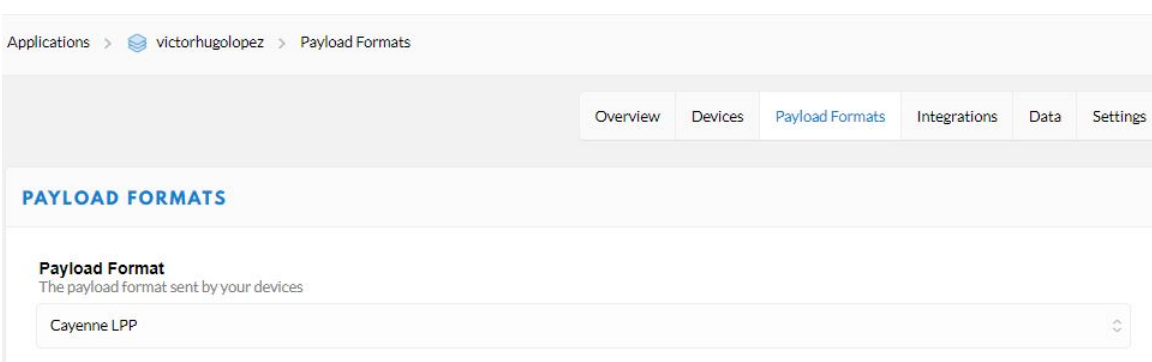


Figure 3.8: Payload Formats Cayenne LPP

3.1.3 Hardware Connection - Temperature, Humidity, and Flame Sensors

There are two sensors connected to LoRa Shield onto the Arduino Uno board (Figure 3.9). These sensors are temperature and humidity known as DHT11, as well as the flame sensor. The pin connections are shown in Table 3.2.

Table 3.2: Pin Connections of the Sensors on TTN Server

Type of Sensor	Sensor Pin	LoRa Shield + Arduino UNO
DHT11	VCC	5V
Temperature	DAT	5th slot (Digital)
and Humidity	GND	GND
	VCC	ICSP (top - right corner)
Flame	GND	GND
	DO	3rd slot (Digital)

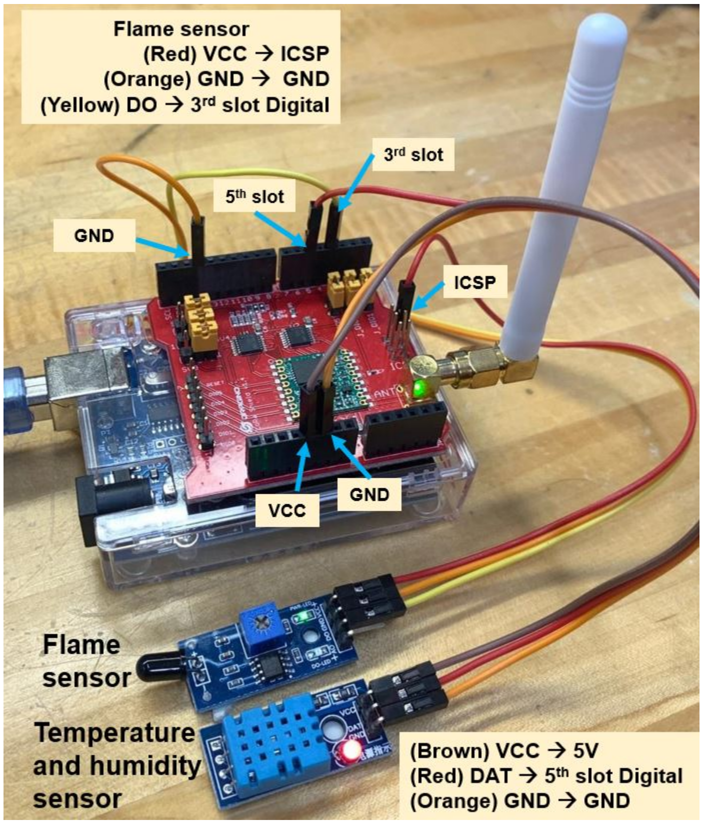


Figure 3.9: Sensors Connected to LoRa Shield onto the Arduino Uno

3.1.4 Software Arduino IDE - Sensor Programming on TTN Server

The Arduino IDE is an open source software with a user-friendly interface to write codes and upload it to the Arduino Uno board. This software can be found on https://www.arduino.cc/en/software. There are important settings that need to be done before writing code.

1. Add URL

File ≫ Preferences ≫ Additional Boards Manager URLs:

http://www.dragino.com/downloads/downloads/YunShield/package_dragino_yun_test_index.json

2. Install board type (Arduino UNO)

Tools ≫ Board ≫ Board Manager and type: "Arduino UNO", and install: *Arduino AVR Boards*

3. Select the correct board

Tools ≫ Board ≫ Arduino AVR Boards ≫ Arduino Uno

4. Install libraries

Sketch ≫ Include Library ≫ Manage Libraries and type:

- "LMIC" [45], and install: MCCI Arduino and MCCI LoRaWAN LMIC Library
- "LoRa", and install: LoRa Node, AntaresLoRaID, LoRaID, LoRa, and LoRa Serialization
- "DHT", and install: DHT sensor library, DHT sensor library for ESPx, and DHTlib

GitHub is one collaboration development platform in which developers share projects, example codes, and libraries. Also, GitHub has example codes for different applications of Arduino, which could be found on [46]. This code is based on "lora_shield_cayenne_and_ttn-otaaClient" example. The code used is provided in Appendix H.

It is essential to check the following setting for each code:

1. Declaration of the pins which must match in the hardware connection (Figure 3.10).

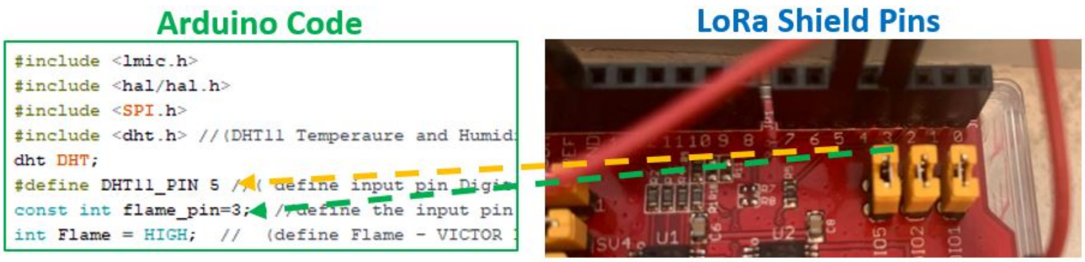


Figure 3.10: Declaration of the Pins

2. Update of the keys which need to be the same as the one generated by TTN (Figure 3.11).

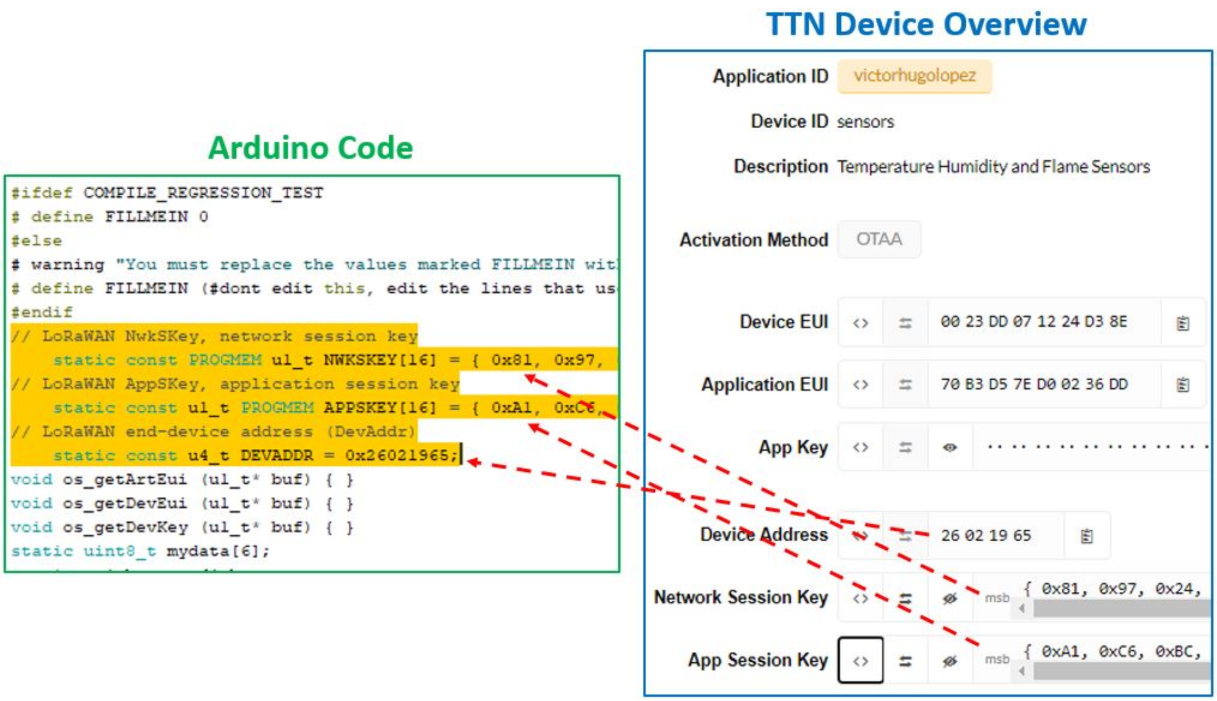


Figure 3.11: Settings Keys

3. Configuration of the transmission frequency, which must match the frequency configured in the gateway (Figure 3.12).

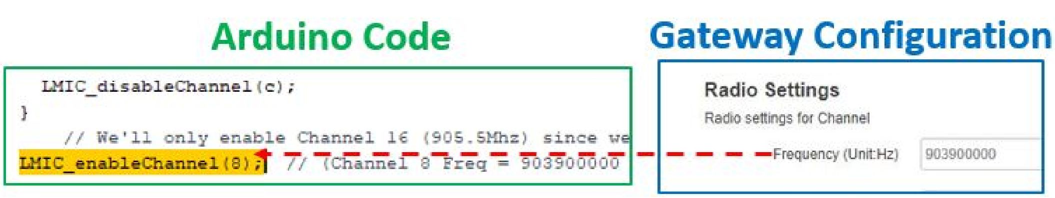


Figure 3.12: Configuration of the Up-link Transmission Frequency

3.2 Field Test Device Configuration on TTN Server

The ***Field Test Device (ARF8124AA)*** was connected on TTN and integrated on Cayenne application server as well. The FTD needs a LoRAWAN gateway to be connected, such as Dragino LG308.

The first step starts with the gateway configuration, choosing the appropriate ***frequency plan*** and ***frequency sub-band***, as well as picking the ***LoRaWAN service provider*** "TTN-router-US-West" (Figure 3.13). Similarly, the gateway ID is needed to register it on TTN. Furthermore, the FTD needs to be registered as a new device on TTN with ABP as an activation method (Figure 3.14).

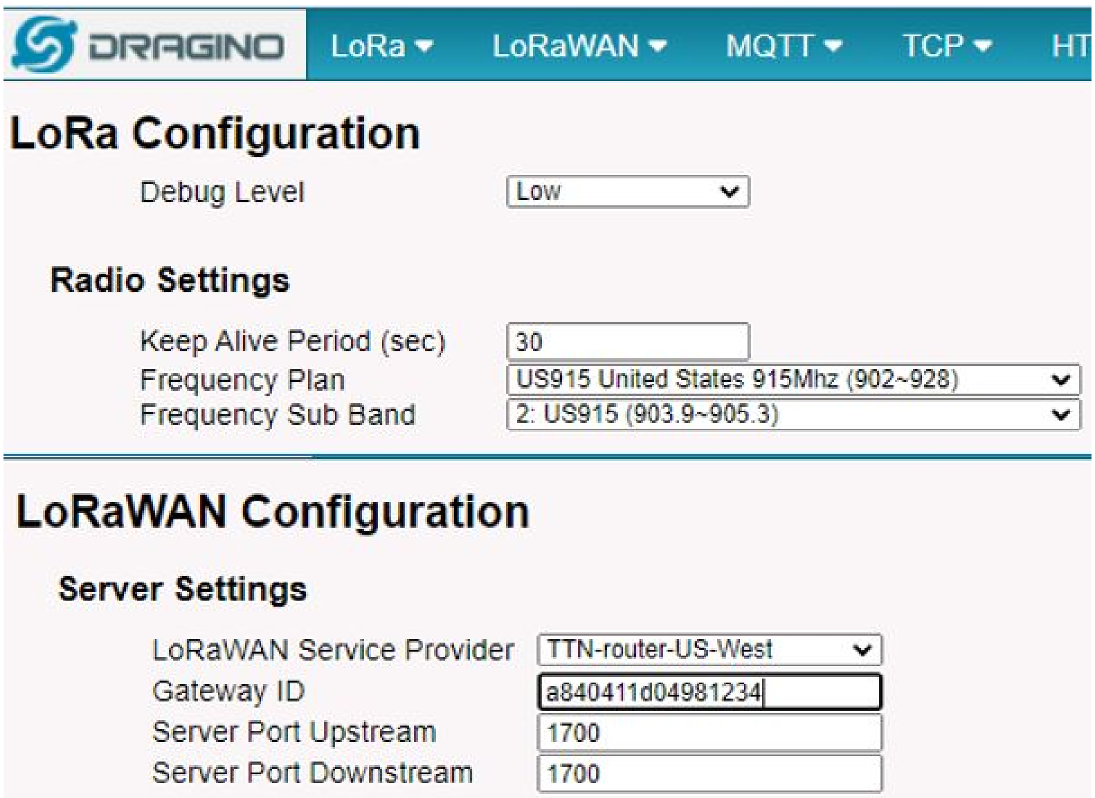


Figure 3.13: Gateway LG308 Configuration at TTN Server

The FTD could be configured by the software IoT Configurator 1.4.1, giving access to the applicative configuration (operation modes, frame transmission period, payload size, etc.) and network

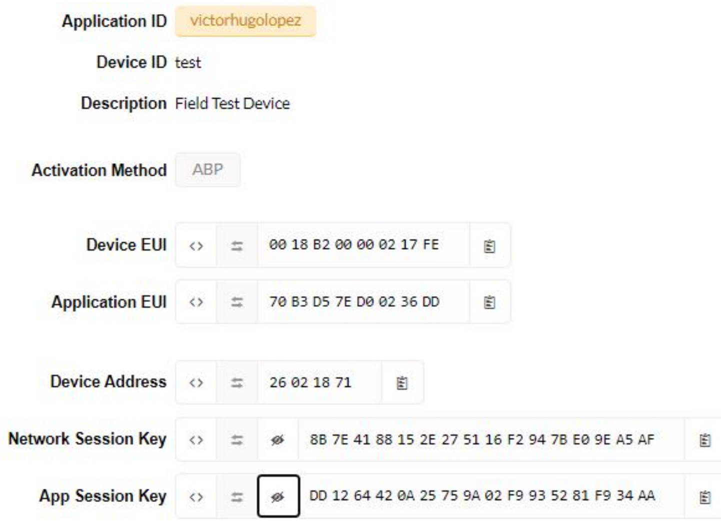


Figure 3.14: Keys generated from TTN Server for FTD with ABP Activation Method

configuration (mode of activation, spreading factor, **Adaptive Data Rate ADR**, and keys). When the ADR is activated on FTD, the NS automatically configures the actual value of the SF. In contrast, if ADR is deactivated, the user has to assign a value to the SF. The Keys generated from TTN need to get into the ABP network configuration (Figure 3.15).

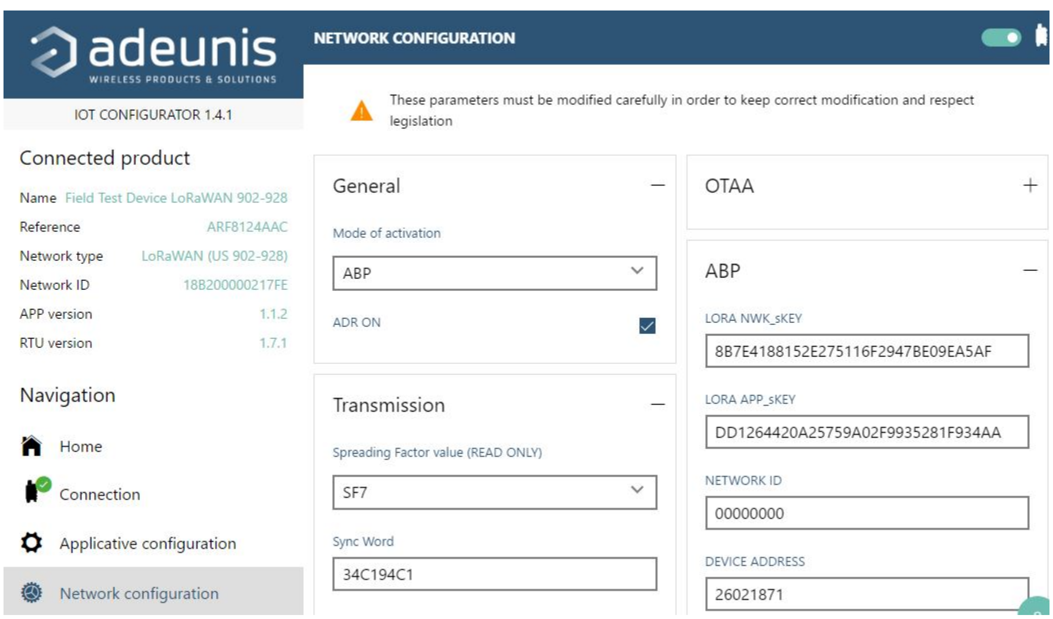


Figure 3.15: IoT Configurator 1.4.1 for FTD

3.3 Cayenne Integration

TTN offers several integrations for ***Application Servers***, which means the TTN forwards the data to the AS. One of these is ***"myDevices Cayenne"*** that allows historical data storage and real-time data visualizing by ***Widgets***. Also, Cayenne allows full management such as remote monitoring, alerts receiving, triggers setting, scheduling, asset tracking, etc. In the main menu of TTN within the application is the integration option, which shows add integration. The Cayenne integration is under ***myDevices*** option that requires setting up the name of the new integration process (Figure 3.16).

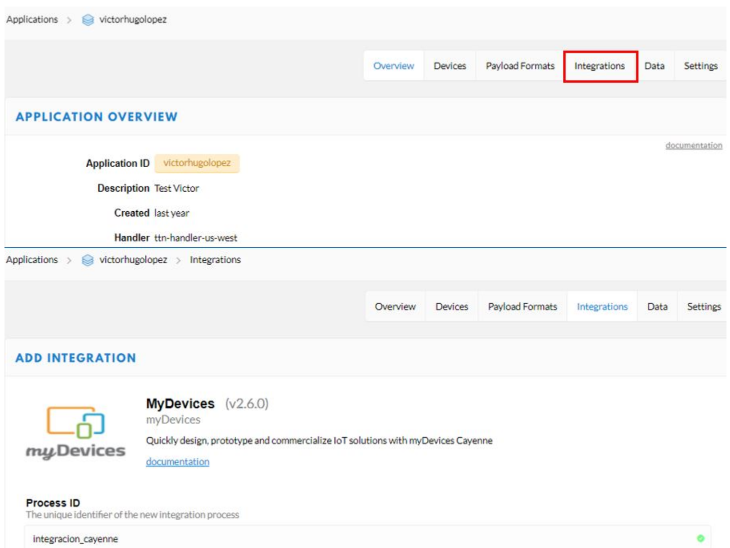


Figure 3.16: MyDevices Cayenne Integration on TTN server

The next step is to sign up for an account on the "myDevices" website [47] and continue with the next steps:

- Add New ≫ Devices & Widgets ≫ Search the sensor for example:

  1. "Dragino Technology Development Kit" (Figure 3.17)

  2. "Adeunis Field Test Device" (Figure 3.18) or

  3. "Cayenne Cayenne LPP" (Any sensor registered on TTN by creating a custom dashboard)

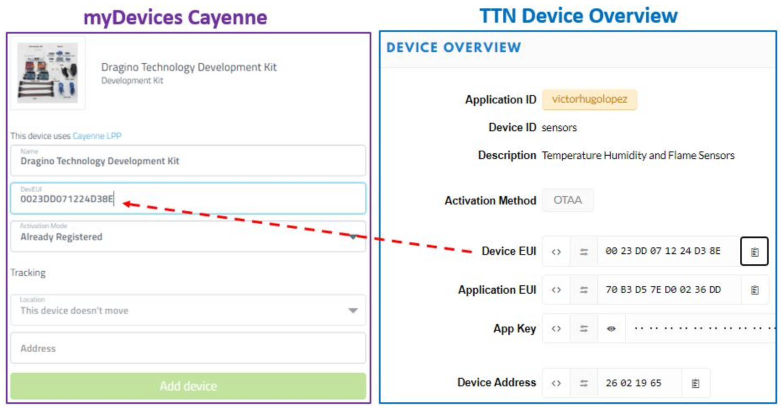


Figure 3.17: Cayenne Integration of Sensors from Dragino Tech Development Kit

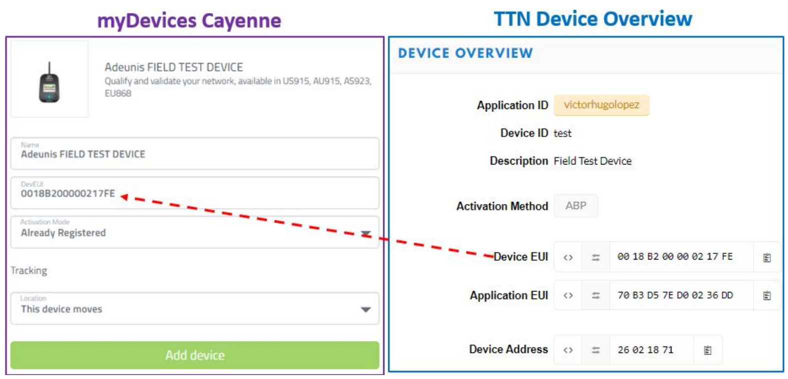


Figure 3.18: Cayenne Integration of Adeunis Field Test Device

- Copy the Device EUI information from TTN to MyDevices Cayenne
- Select “Already Registered” at Activation Mode
- Set up the location

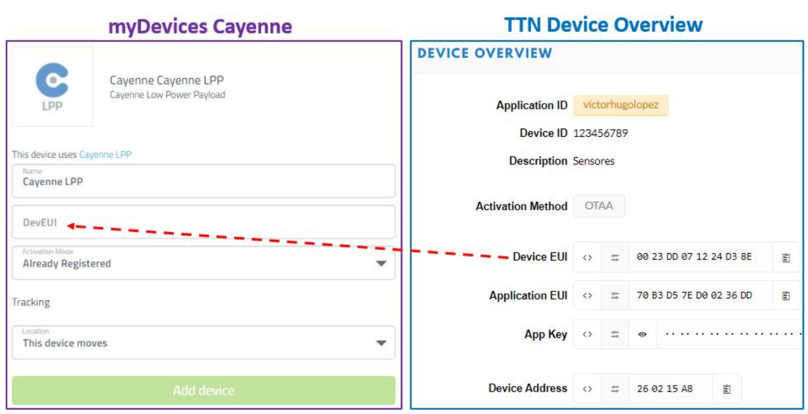


Figure 3.19: Cayenne Integration of Any Sensor Registered at TTN Server

3.4 IoT Application on ThingSpeak Server

The IoT application is carried out using the Dragino LG01-N LoRa gateway, which forwards the sensors' messages to ***"ThingSpeak"*** IoT server. This application also uses different sensors such as temperature, humidity, and a flame sensor, which are connected on the LoRa shield onto the Arduino Uno board. The communication among gateway and ***"ThingSpeak"*** is via Internet ***Message Queuing Telemetry Transport (MQTT)*** protocol. MQTT is a messaging protocol used to publish and subscribe messages into the ***IoT***. The Arduino code uses the ***LoRa*** library, which allows the LoRa's communication among sensor and gateway. Consequently, the software ***Wireshark*** (Sniffer Network Protocol Analyzer) is connected to the gateway to measure packets' delay from sensors. The architecture of this IoT application is shown in Figure 3.20.

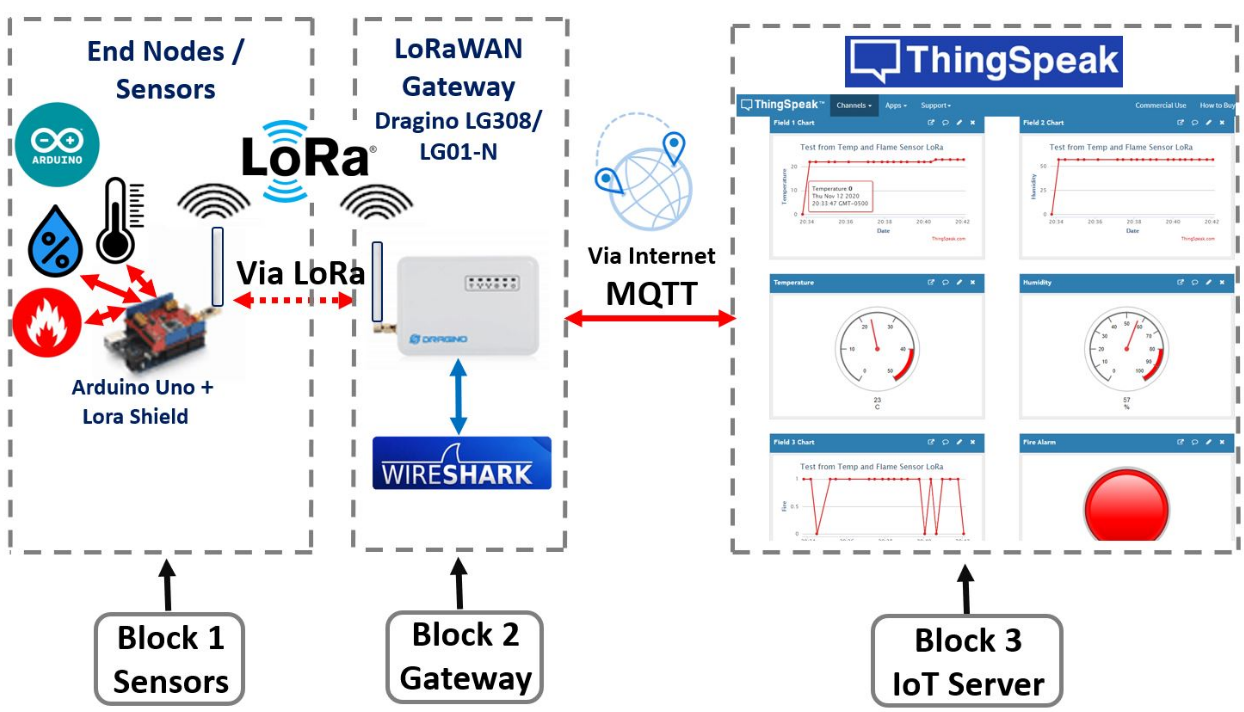


Figure 3.20: Architecture of IoT Application on "ThingSpeak" Server

The steps to follow are detailed below [48]:

1. Setup an account in ThingSpeak IoT Server(https://thingspeak.com/login).

2. Create a **New Channel** (Figure 3.21).

   (Menu Channels ≫ My Channels ≫ New Channel)

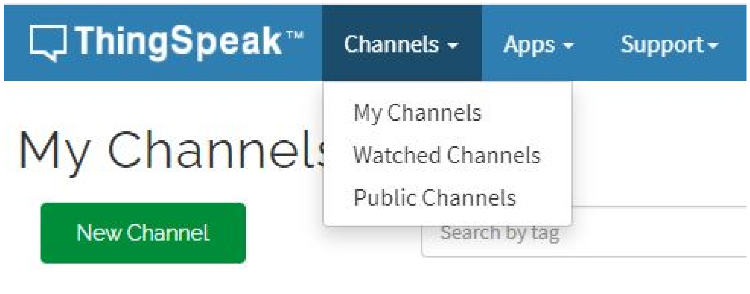


Figure 3.21: New Channel on ThingSpeak server

3. Enable **Field1**: "Temperature"; **Field2**: "Humidity"; **Field3**: "Fire" (Figure 3.22).

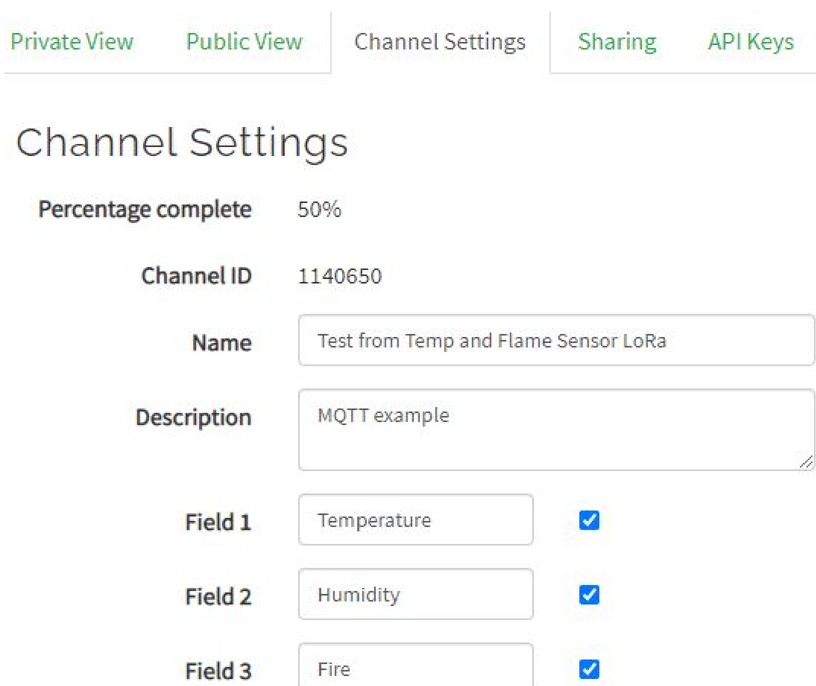


Figure 3.22: Channel Settings on ThingSpeak Server

4. Test the Up-link communication via MQTT using the software ***MQTT fx*** from PC. The following information is needed from the ThingSpeak server (Figure 3.23).

   ▷ (Menu: Channels ≫ My Channels ≫ Settings)

   • **Channel ID:** 1140650

   • **Author:** mwa0000019491111

Figure 3.23: Channel ID and Author on ThingSpeak Server

   ▷ Menu: My Profile

   • **MQTT API Key:** DXZXXYCT4BDURSQ5 (Figure 3.24)

Figure 3.24: MQTT API Key on ThingSpeak Server

5. Set up the software ***MQTT fx*** under **MQTT Broker Profile Settings**.

   • **Broker Address:** mqtt.thingspeak.com

   • **Broker Port:** 1883

   • **Client ID:** MQTT_Victor

6. Set up the software ***MQTT fx*** under **User Credential** and click on the **Connect** button (Figure 3.25).

   • **User Name:** mwa000001949111

   • **Password:** DXZXXYCT4BDURSQ5

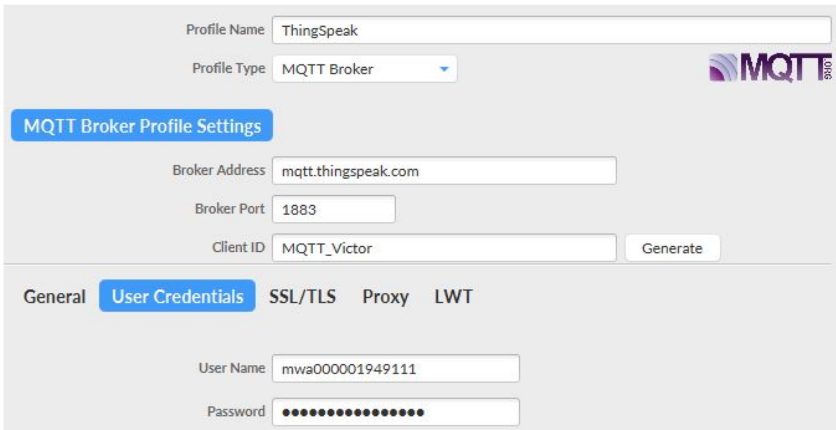


Figure 3.25: MQTT Broker Profile Settings

7. Type a Publish command with the information provided below and click on the **Publish** button (Figure 3.26).

   ▷ Information from ThingSpeak Server:

   • **Channel ID:** 1140650 (Channels ≫ My Channels ≫ Settings)

   • **Write API Key:** ZDRTBVFV43D5QB3M (Channels ≫ My Channels ≫ API Keys)

   ▷ Configuration on ***MQTT fx***

   • **QoS:** QoS 0 button

   • **Type 1** ≫ channels/1140650/publish/ZDRTBVFV43D5QB3M

   • **Type 2** ≫ field1=60&field2=40&status=MQTTPUBLISH

8. Check the update data on the ThingSpeak channel (Figure 3.27).

9. Test into Dragino LG01-N gateway from PC.

   ▷ Install PuTTY Configuration and click on **Open** button using below information:

   • **Dragino IP**: 10.130.1.1

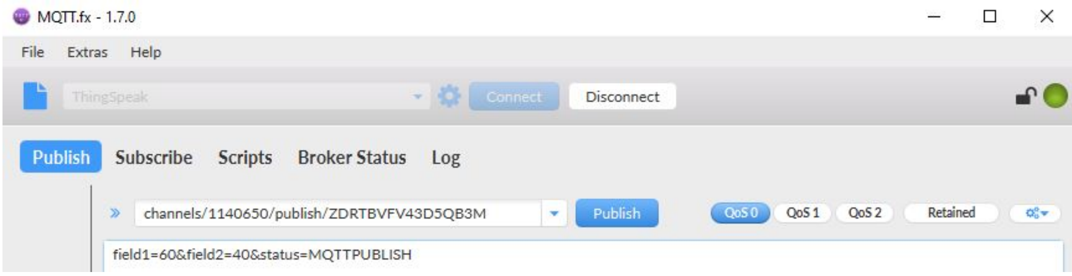


Figure 3.26: MQTT Publish Command

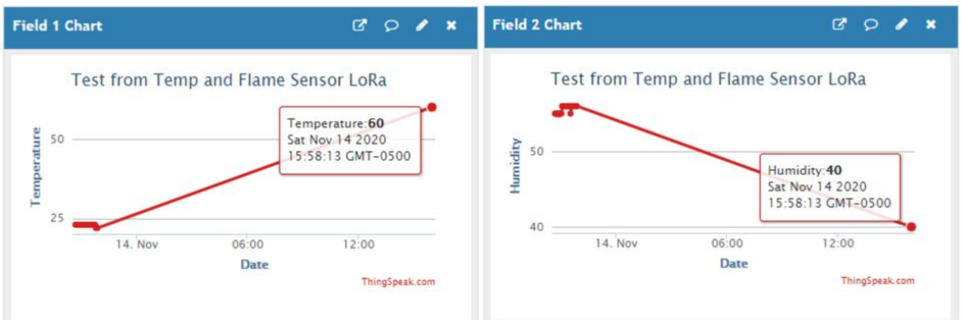


Figure 3.27: Update Data on ThingSpeak Channel by MQTT Publish Command

- **Port**:22

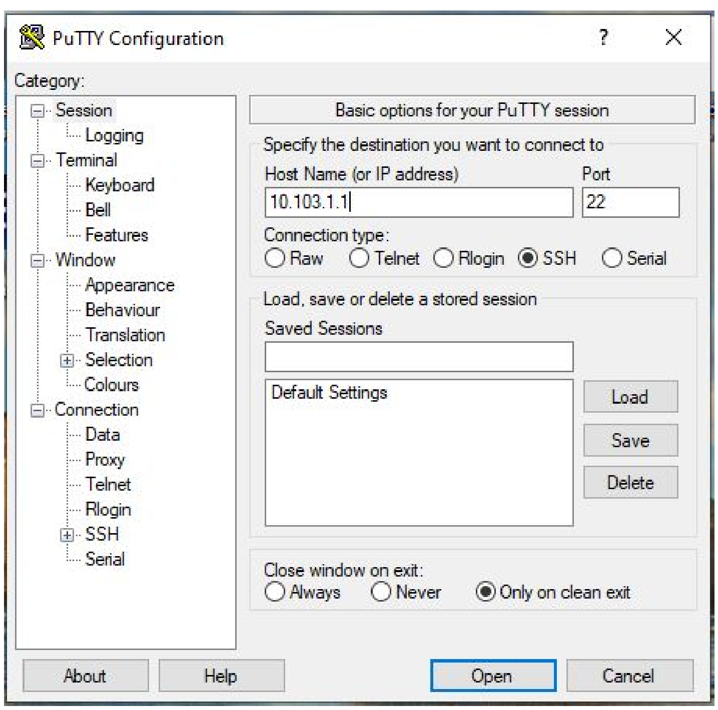


Figure 3.28: PuTTY Configuration

▷ Dragino LG01-N gateway has a built-in Linux utility **mosquitto_pub** (Figure 3.29) commands, which allows publishing data to ThingSpeak. Therefore, it needs to login and provide mosquito command.

Therefore, login and type mosquitto commands are:

- **User:** root
- **Password:** dragino
- **Type command** ≫

mosquitto_pub -h mqtt.thingspeak.com -p 1883 -u mwa0000019491111

-P DXZXXYCT4BDURSQ5 -I dragino_Client

-t channels/1140650/publish/ZDRTBVFV43D5QB3M

-m "field1=80&field2=20&status=MQTTPUBLISH"

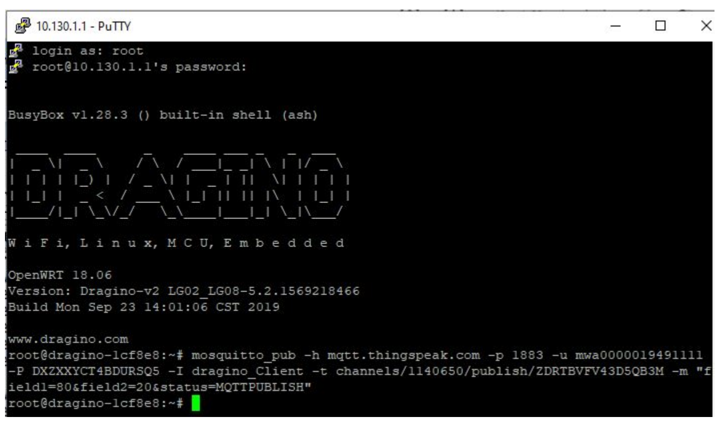


Figure 3.29: Linux Mosquitto Command to Publish Data at the ThingSpeak Channel

10. Check the ThingSpeak channel for the updated data from temperature and flame sensors (Figure 3.30).

11. Hardware -Dragino LG01-N Gateway Configuration on ThingSpeak Server.

    ▷ Menu: Service ≫ LoRaWAN Gateway

    - **IoT Service:** "LoRaRAW forward to MQTT server" (Figure 3.31)

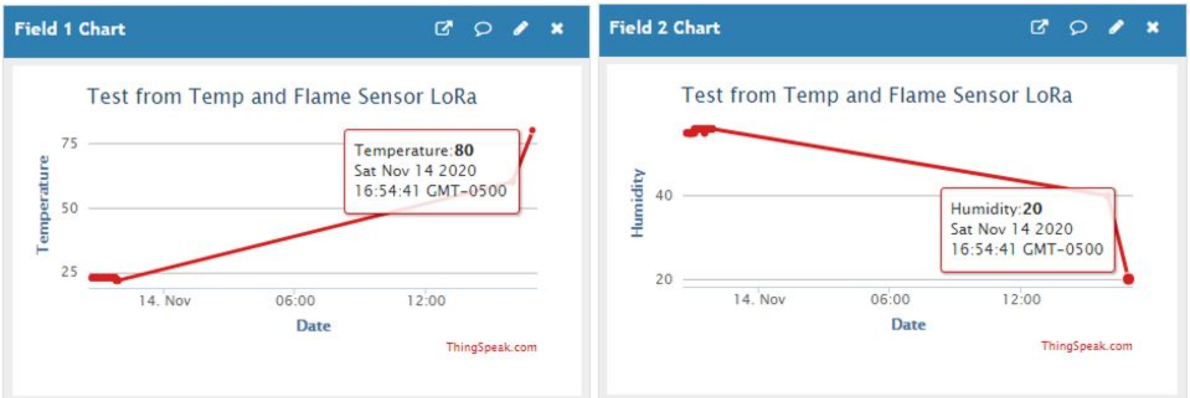


Figure 3.30: Updated Data on ThingSpeak Channel by Mosquitto Command

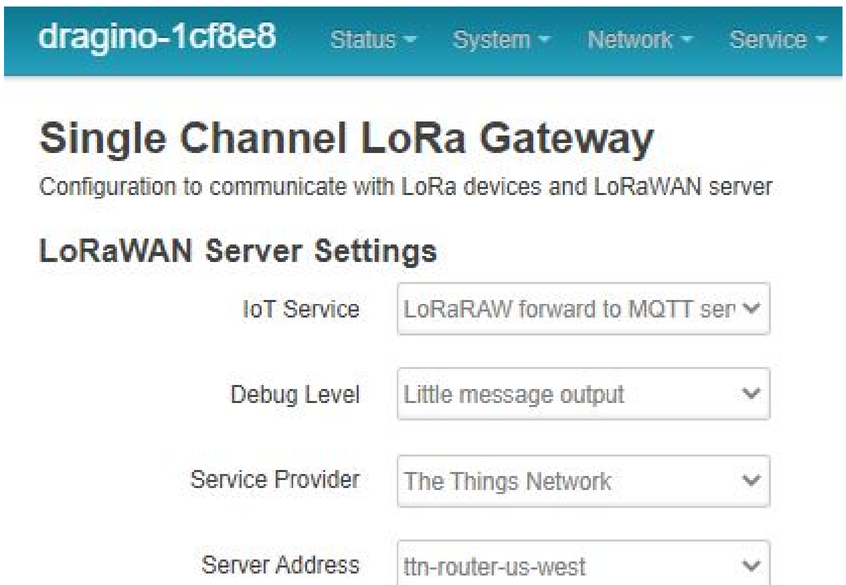


Figure 3.31: Gateway LoRaWAN Server Settings on ThingSpeak

- **Frequency (Unit:Hz):** “903900000” (Figure 3.32)
- **Spreading Factor:** “SF7”
- **Coding Rate:** “4/5”
- **Signal Bandwidth:** “500 KHz”
- **Preamble Length:** “8”
- **LoRa Sync Word:** “52” (Value 52(0x34) for LoRaWAN)

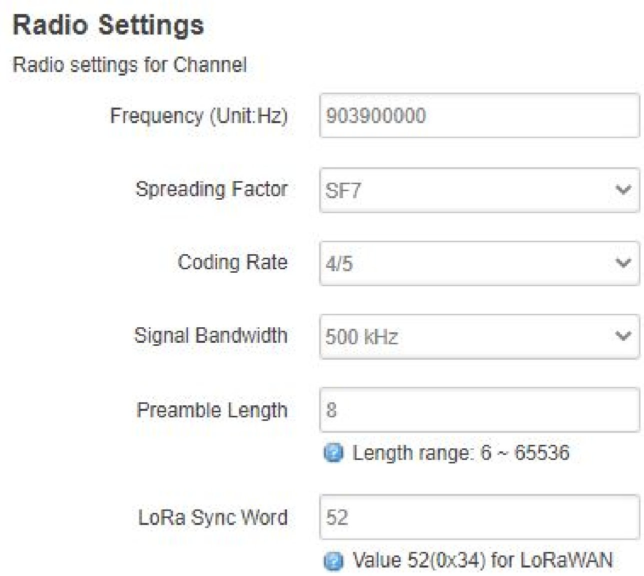


Figure 3.32: Gateway Radio Settings on ThingSpeak

▷ Menu: Service ≫ MQTT ≫ Configure MQTT Server (Figure 3.33)

- **Select Server:** "ThingSpeak MQTT"
- **User Name [-u]:** "mwa0000019491111"
- **Password [-P]:** "DXZXXYCT4BDURSQ5"
- **Client ID [-i]:** "QoS 0"

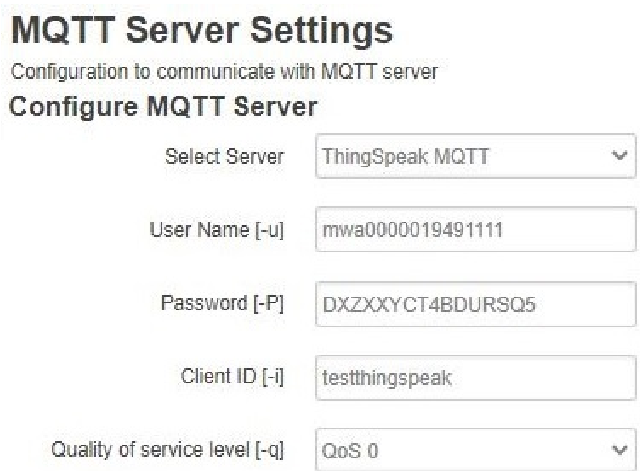


Figure 3.33: Gateway MQTT Server Settings

▷ Menu: Service ≫ MQTT ≫ MQTT Channel and click on the **Add** button (Figure 3.34)

- **Local Channel ID:** "5678"
- **Remote Channel ID:** "1140650"
- **Write API Key:** "ZDRTBVFV43D5QB3M"

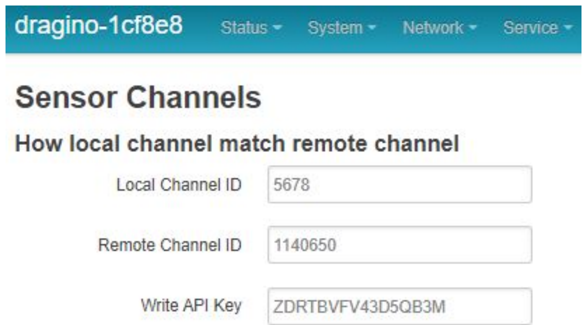


Figure 3.34: Gateway Sensor Channels

12. Hardware Connection - Temperature, Humidity, and Flame Sensors at the ThingSpeak Server.

▷ There are two sensors (Temperature & Humidity and Flame) connected to LoRa Shield onto the Arduino Uno board (Figure 3.35). The pin connection is shown in Table 3.3.

Table 3.3: Connection Pins of the Sensors on ThingSpeak Server

Type of Sensor	Sensor Pin	LoRa Shield + Arduino UNO
DHT11 Temperature and Humidity	VCC DAT GND	5V 0 slot (Analog) GND
Flame	VCC GND DO	ICSP (top - right corner) GND 3rd slot (Digital)
LEDs and Buzzer	Green LED Red LED Buzzer	6th slot (Digital) 5th slot (Digital) 8th slot (Digital)

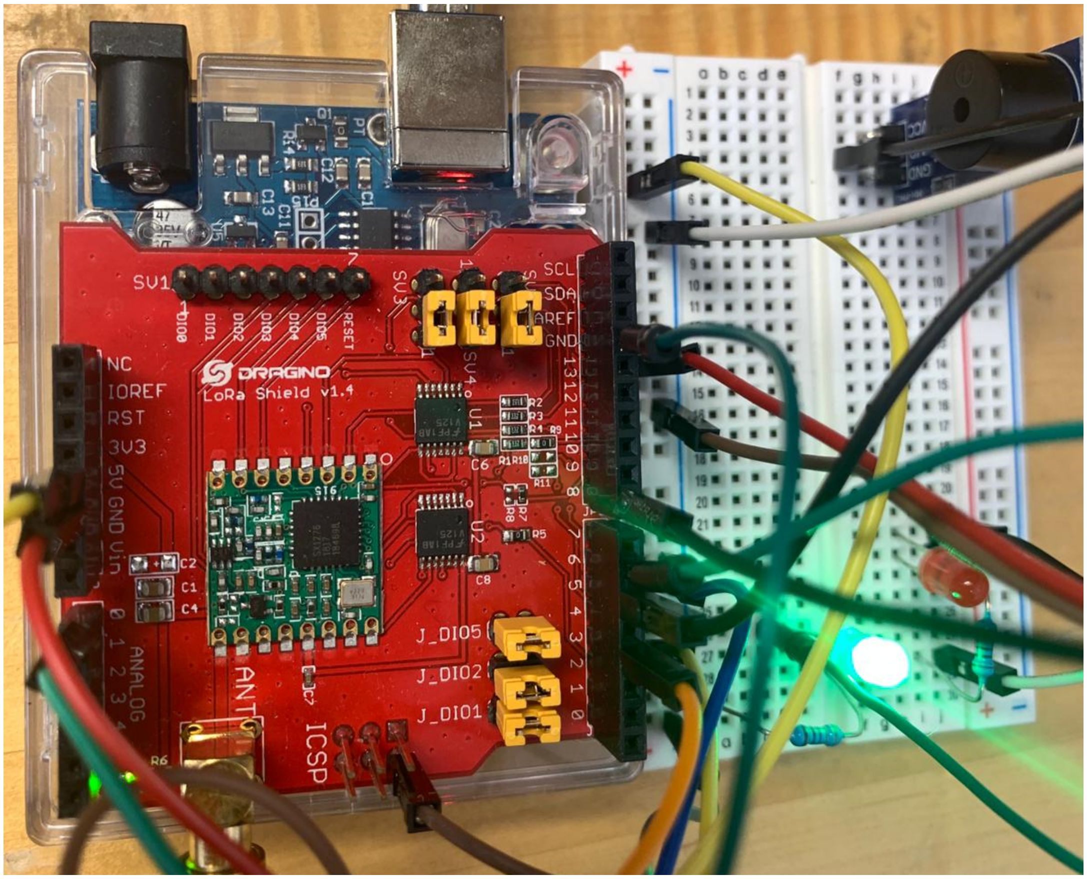


Figure 3.35: Sensors Connected to LoRa Shield on ThingSpeak Server

13. Software Arduino IDE - Sensor Programming to ThingSpeak.

    This code is based on “MQTT_Client_to_ThingSpeak.ino” example [49].

    The code used for configuring the sensors on Arduino Uno board is given in Appendix I. Also, it is essential to check the following setting:

    • **Hardware connection** (Figure 3.36)

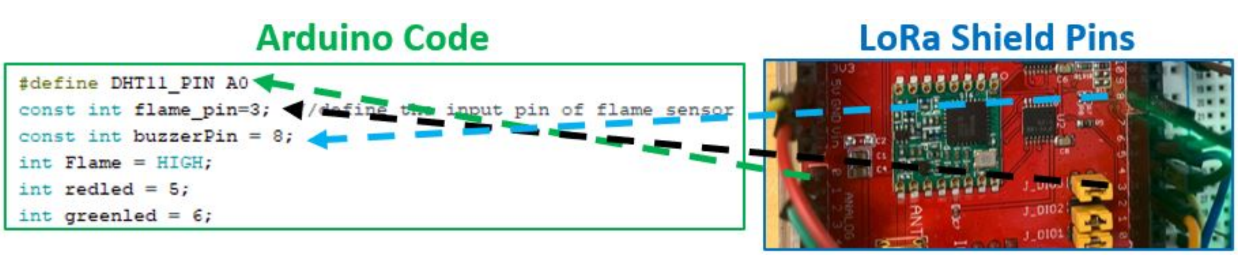


Figure 3.36: Declaration of the Pins on ThingSpeak Server

• **MQTT Channel** (Figure 3.37)

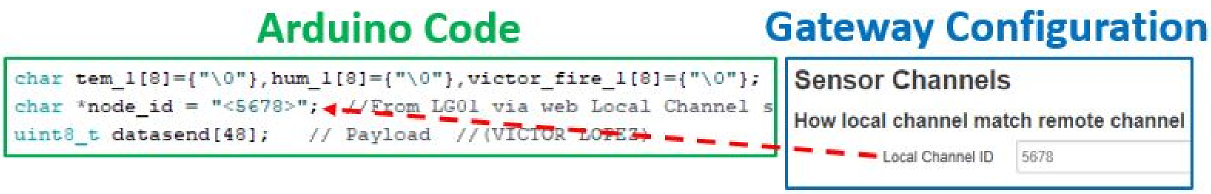


Figure 3.37: Local Channel ID Setting on ThingSpeak Server

• **Radio Settings** (Figure 3.38)

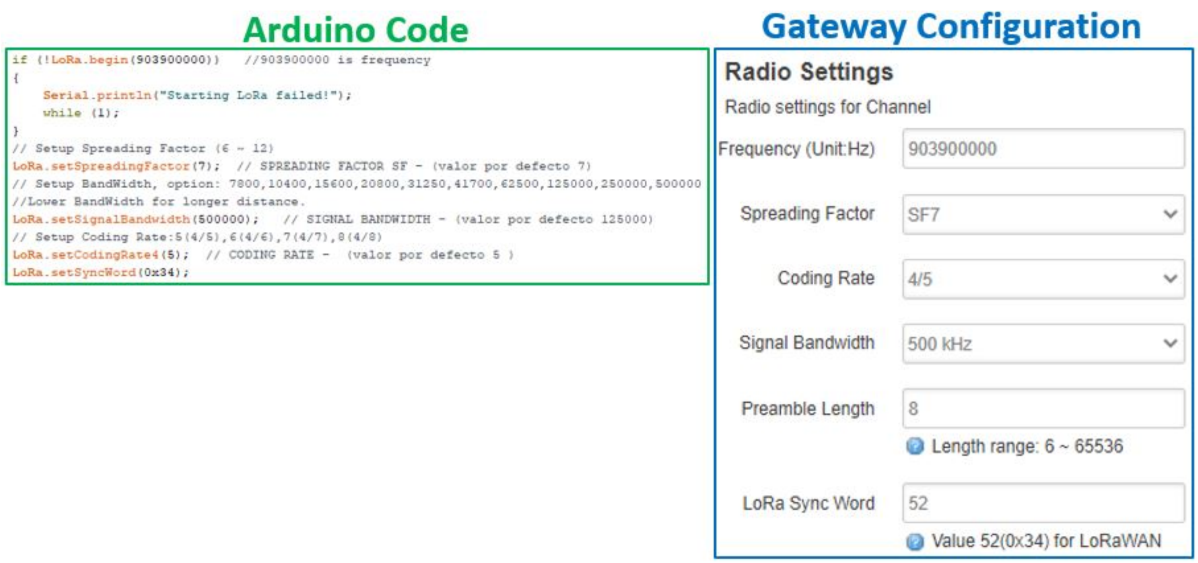


Figure 3.38: Radio Settings on ThingSpeak Server

This chapter detailed the methodology used to implement an IoT application to TTN and ThingSpeak servers. In addition, it showed all the configurations made in sensors, gateways, and IoT servers to establish a LoRa communication between a sensor node and cloud server.

Chapter 4

Results and Discussion

This chapter presents the graphical visualization of the sensors' data (temperature, humidity and frame) from the TTN (integrated with Cayenne) and ThingSpeak server. In addition, the performance study was carried out for both indoor and outdoor applications in terms of ***Time on Air***, communication range, payload, etc. The indoor test focuses on the measurement of Time on Air for different configurations of the LoRa gateway. A total of ***348*** configurations were made among SF, BW, CR, and payload. Furthermore, a comparison of ToA was carried out between the experimental and theoretical values. The theoretical values were generated by the LoRa modem calculator tool. This comparison is performed with an independent ***t-test*** statistics model to determine the significant difference between the experimental and the theoretical values.

4.1 Results of IoT Application on The Things Network Server Integrated with Cayenne

The sensors' data is received by TTN, which sends the information to the Cayenne application server for graphical visualization. The application data shows information about arrival time, frequency, data rate, coding rate, channel, RSSI, SNR, and estimated airtime within each packet (Figure 4.1). The dashboard on Cayenne presents a summary of all connected sensors, as well as RSSI and SNR levels (Figure 4.2).

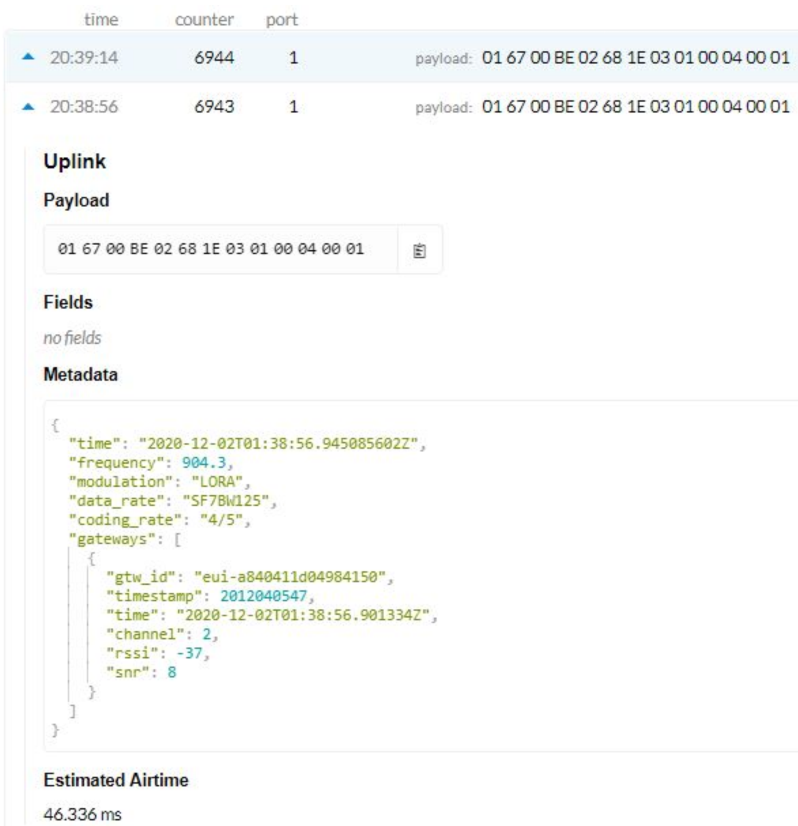


Figure 4.1: Packet Received by The Things Network

All data is stored on the Cayenne platform and can be viewed using standardized plots. For example, temperature, and humidity are standardized in Figure 4.3.

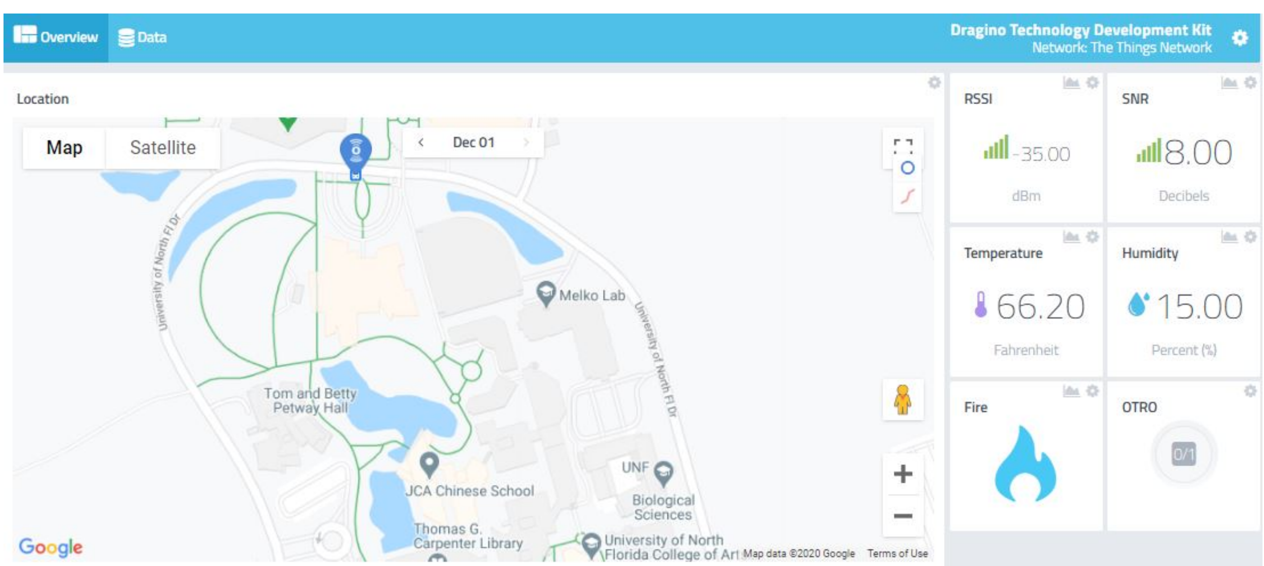


Figure 4.2: Cayenne Dashboard Overview

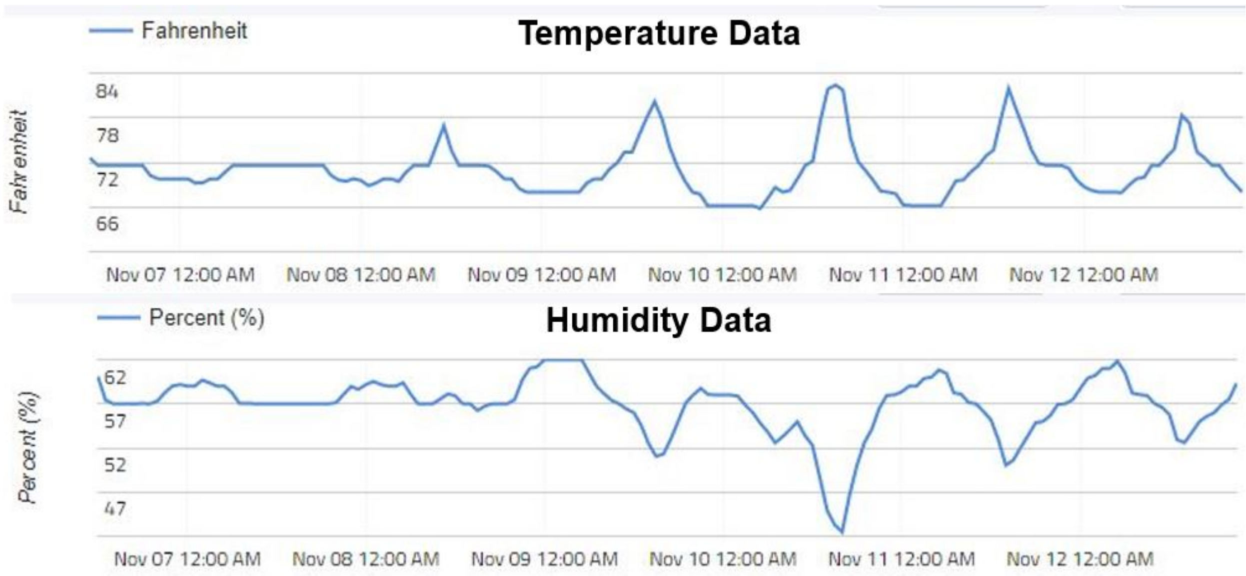


Figure 4.3: Temperature and Humidity on Cayenne Server

Additionally, settings were configured in the server to push the information from the Cayenne's server to our mobile devices. The data can be viewed through the Cayenne mobile app, and triggers can be configured to receive text and email notifications (Figure 4.4).

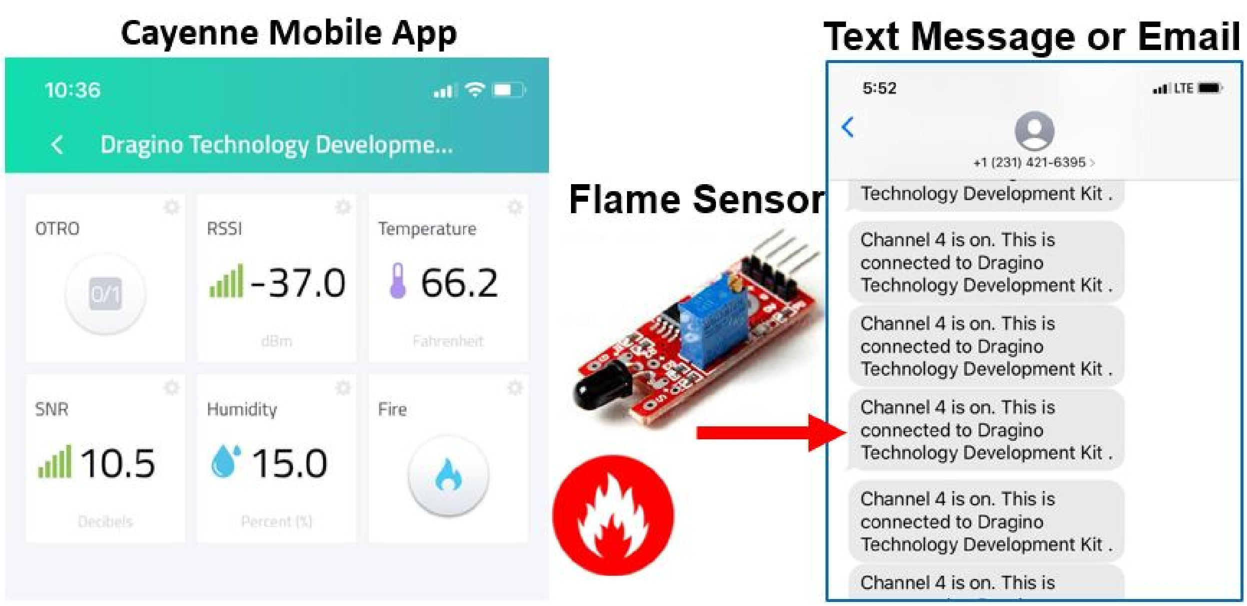


Figure 4.4: Data on Cayenne Mobile App

The flame sensor has been tested against illumination from sunlight (Figure 4.5). This sensor is activated when sunlight's illumination reaches 2308.0 (lux) from 12:40 PM to 4:40 PM. Therefore, the built-in potentiometer must be calibrated before final installation.

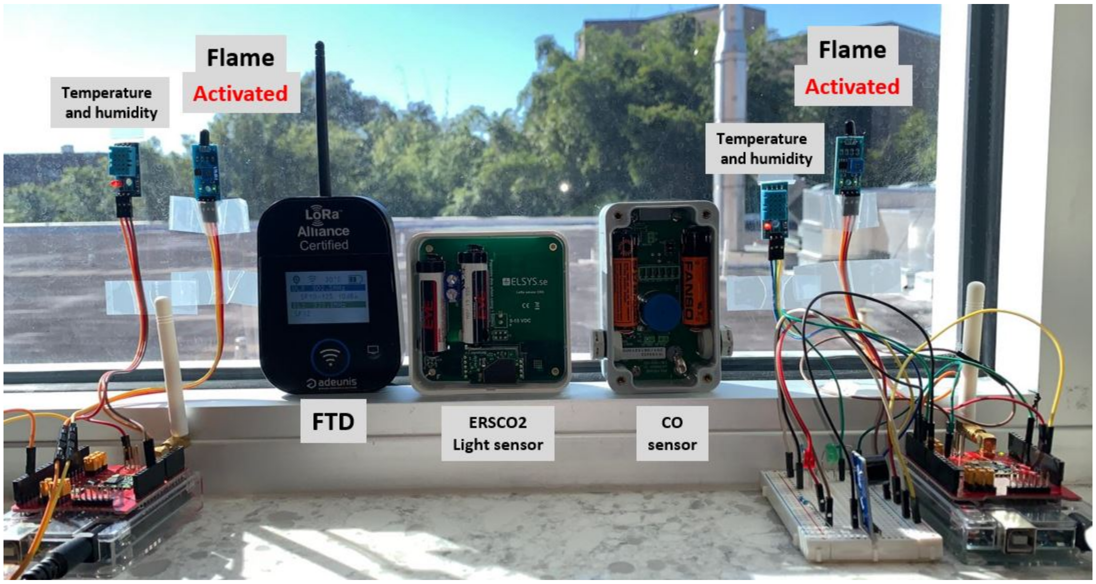


Figure 4.5: Flame Sensor Test Against Sunlight Illumination

Also, the ***"LoRa Elsys.se ERSCO2"*** sensor was connected to the ***"IoI in a Box (myDevices)"*** server which shows the luminosity trend in Figure 4.6.

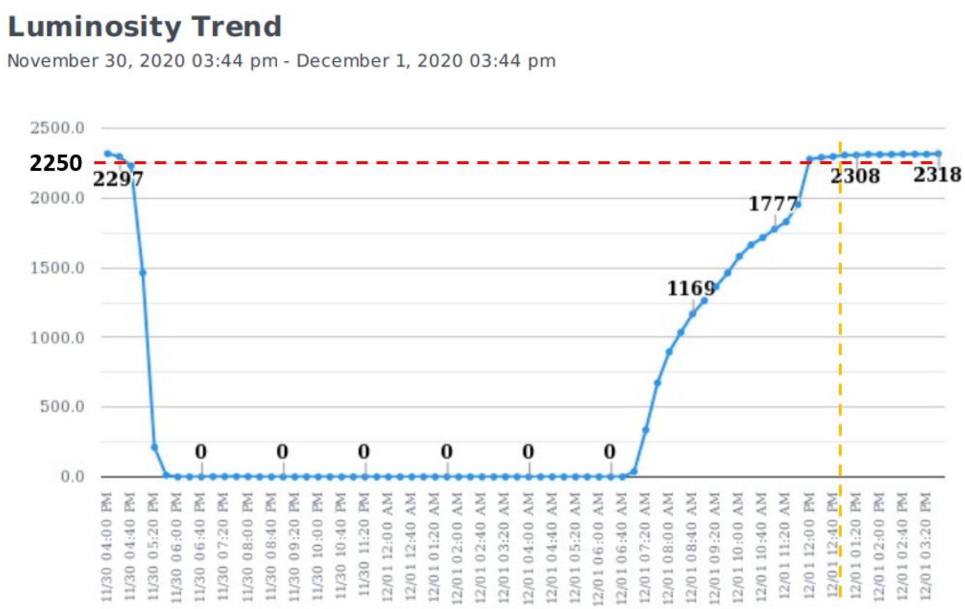
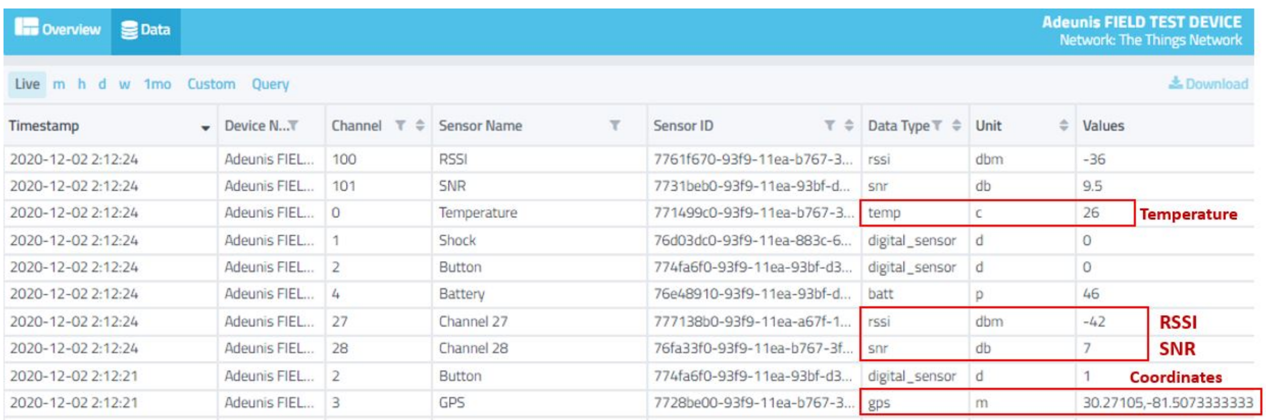


Figure 4.6: Luminosity Trend on "IoT in a Box (myDevices)" Server

4.2 Results of Field Test Device Configuration on TTN Server Integrated with Cayenne

Cayenne dashboard exhibited the FTD's data sent as RSSI, SNR, temperature, battery status, and coordinates (latitude and longitude) (Figure 4.7).

This data can also be viewed through Cayenne mobile app (Figure 4.8). Since FTD provides a numeric display of GPS, SNR and SF, therefore, this device was used for carrying out outdoor measurements.



Timestamp	Device N...	Channel	Sensor Name	Sensor ID	Data Type	Unit	Values
2020-12-02 2:12:24	Adeunis FIEL...	100	RSSI	7761f670-93f9-11ea-b767-3...	rssi	dbm	-36
2020-12-02 2:12:24	Adeunis FIEL...	101	SNR	7731beb0-93f9-11ea-93bf-d...	snr	db	9.5
2020-12-02 2:12:24	Adeunis FIEL...	0	Temperature	771499c0-93f9-11ea-b767-3...	temp	c	26
2020-12-02 2:12:24	Adeunis FIEL...	1	Shock	76d03dc0-93f9-11ea-883c-6...	digital_sensor	d	0
2020-12-02 2:12:24	Adeunis FIEL...	2	Button	774fa6f0-93f9-11ea-93bf-d3...	digital_sensor	d	0
2020-12-02 2:12:24	Adeunis FIEL...	4	Battery	76e48910-93f9-11ea-93bf-d...	batt	p	46
2020-12-02 2:12:24	Adeunis FIEL...	27	Channel 27	777138b0-93f9-11ea-a67f-1...	rssi	dbm	-42
2020-12-02 2:12:24	Adeunis FIEL...	28	Channel 28	76fa33f0-93f9-11ea-b767-3f...	snr	db	7
2020-12-02 2:12:21	Adeunis FIEL...	2	Button	774fa6f0-93f9-11ea-93bf-d3...	digital_sensor	d	1
2020-12-02 2:12:21	Adeunis FIEL...	3	GPS	7728be00-93f9-11ea-b767-3...	gps	m	30.27105,-81.5073333333

Figure 4.7: Cayenne Live Data from Field Test Device

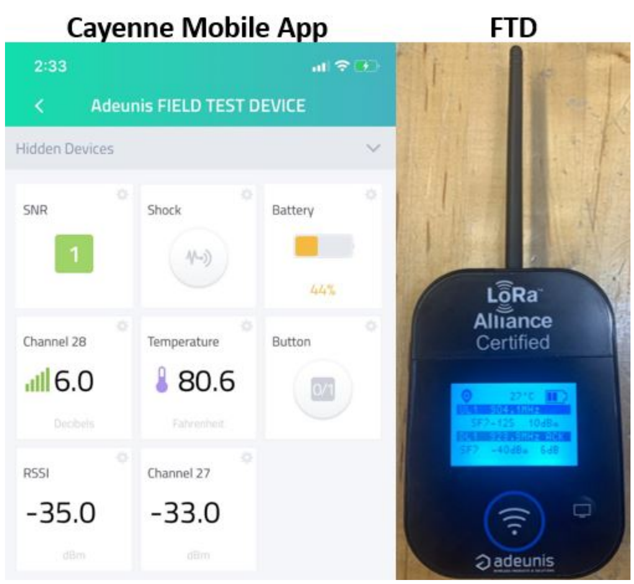


Figure 4.8: FTD on Cayenne Mobile App

4.3 Results of IoT Application on ThingSpeak Server

A channel was configured for the IoT ThingSpeak server with three fields: temperature, humidity and fire. Figure 4.9 shows the historical (top) and the instantaneous (middle) values of the sensor's data. The flame sensor has two states: "0" means activated and "1" deactivated. Therefore, when the sensor sends a "0", the ThingSpeak server interprets it as a fire alarm.

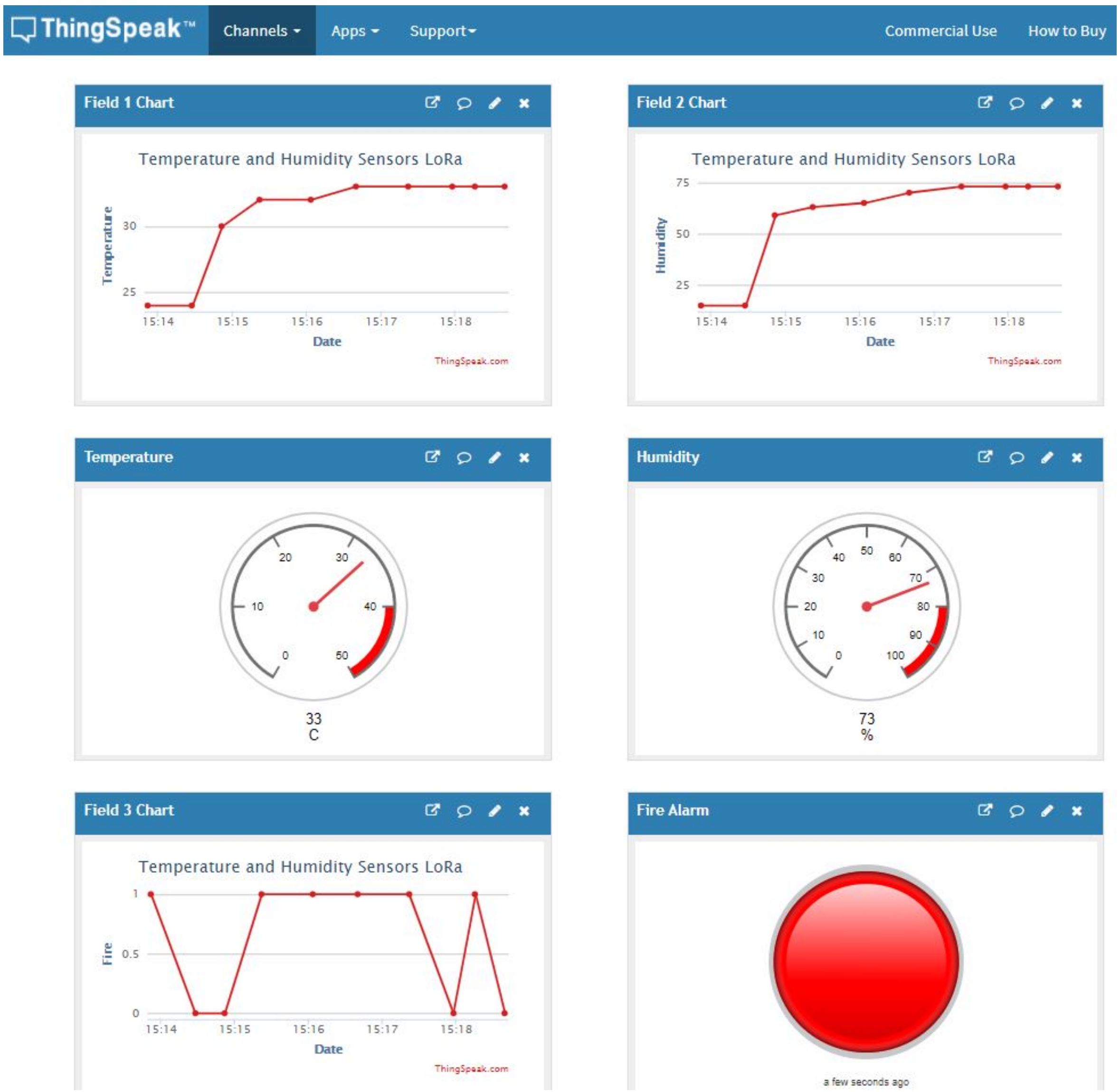


Figure 4.9: Channel Viewing on ThingSpeak Server

4.4 Indoor Environment - Experimental vs. Theoretical

The performance evaluation was carried out by the Dragino LG01-N gateway, which uses a single channel LoRa communication to receive messages from the sensors. First, the ***serial monitor*** tool was used to visualize the time when the sensor sends the message. Second, a wired connection is made between the gateway and PC to access the ***gateway's Linux console***. Third, the software ***Wireshark*** indicates the arrival time of the message (Figure 4.10). Finally, the ***time on air*** is calculated.

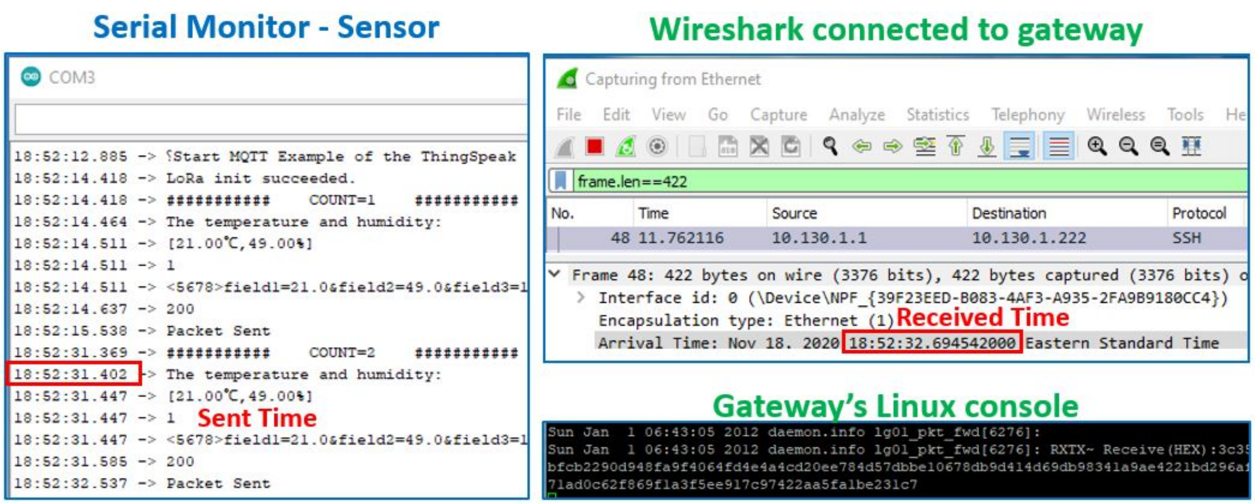


Figure 4.10: Experimental Time on Air

There are 120 different radio settings (Appendix J) between SF, signal BW, and CR (Table 1.6). These radio settings were made on both sides (sensor and gateway) to produce LoRa communication. Consequently, 120 ToA were obtained for a given distance of 10 m. According to the FCC, the ToA must be fewer than 400 milliseconds; therefore, only 57 (Figure 4.13) (Appendix K) of 120 combinations met this criterion. The ToA measurements were taken for different payload lengths: 29, 51, 62, 84 and 118 bytes. (4.11). Table 4.1 summarizes different combinations used during experimentation.

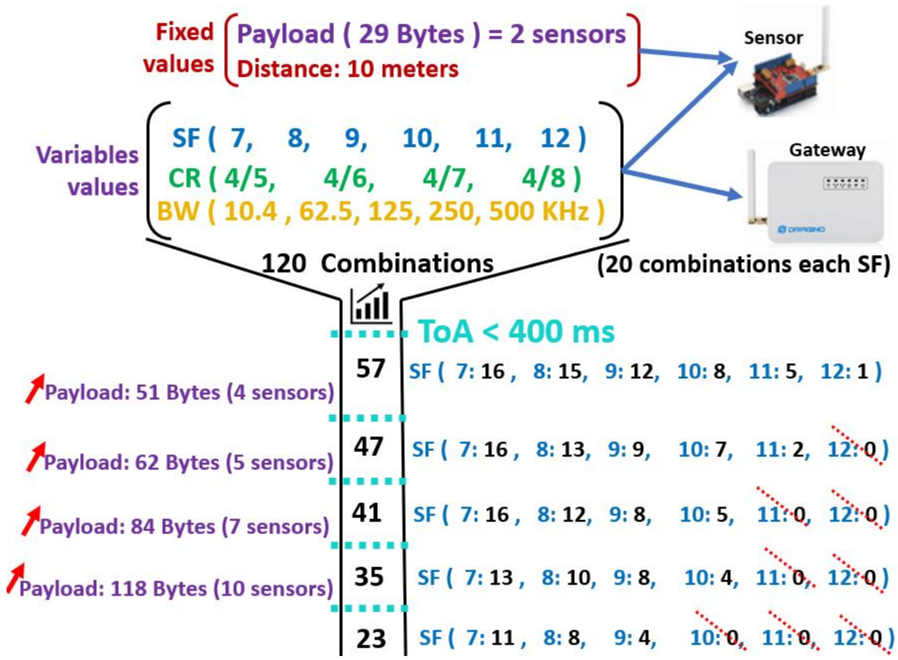


Figure 4.11: Summary of Datasets Used for Experimentation with Different Payload Values

Table 4.1: Tabular Representation of Datasets for Which ToA $<$ 400 ms for each SF

Spreading Factor (SF)	2 Sensors 29 Bytes	4 Sensors 51 Bytes	5 Sensors 62 Bytes	7 Sensors 84 Bytes	10 Sensors 118 Bytes
7	16	16	16	13	11
8	15	13	12	10	8
9	12	9	8	8	4
10	8	7	5	4	0
11	5	2	0	0	0
12	1	0	0	0	0
Combinations for which ToA $<$ 400 ms	57	47	41	35	23

Figure 4.12 illustrates the experimental ToA obtained using different combinations of SF, CR and bandwidth for 29 bytes payload. With these combinations, the data rate varies from 24.3 bps (for SF = 12, CR = 4/5 and BW = 10.4 kHz) to 22 kbps (for SF = 7, CR = 4/5 and BW = 500 kHz). From this figure, the following observations were obtained:

- Minimum ToA = 28.4202 ms with SF= 7, CR= 4/5, and BW= 500 KHz
- Maximum1 (all BW) ToA = 4558.43 ms with SF=9, CR= 4/8, and BW= 10.4 KHz
- Maximum2 (BW= 125) ToA = 2251.086 ms with SF=12, CR= 4/8, and BW= 125 KHz
- $\uparrow$ (increase) SF $\Rightarrow$ ToA $\uparrow$ (increase)
- $\uparrow$ (increase) CR $\Rightarrow$ ToA $\uparrow$ (increase)
- $\uparrow$ (increase) BW $\Rightarrow$ ToA $\downarrow$ (decrease)
- $\uparrow$ (increase) Payload $\Rightarrow$ ToA $\uparrow$ (increase)

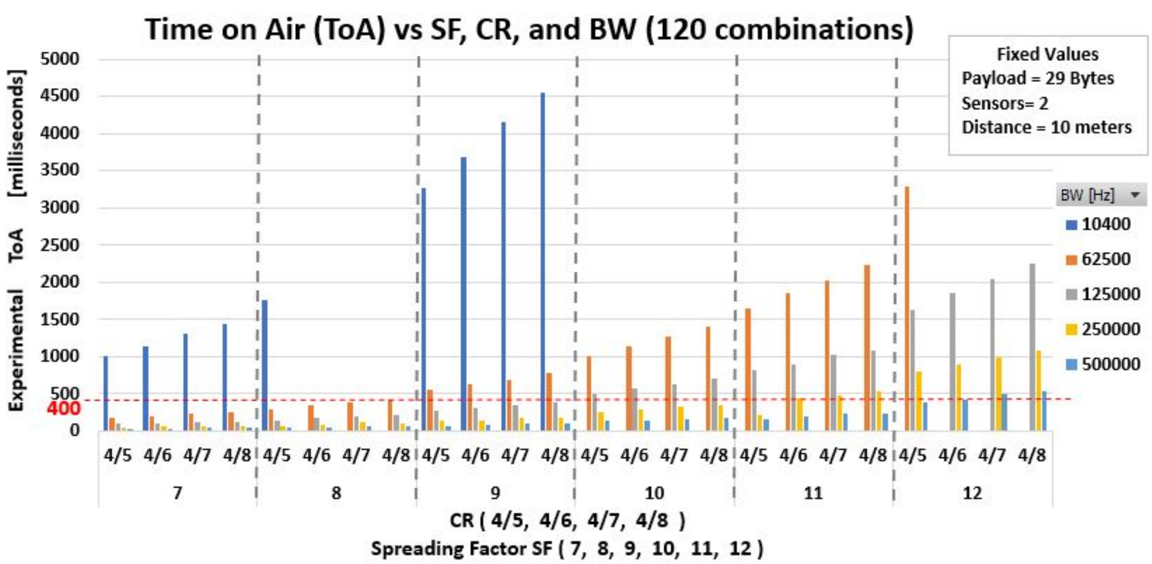


Figure 4.12: ToA vs. SF, CR, and BW (120 Combinations)

Following observations have been made from Figures 4.12 and 4.13:

1. For a given range, payload, BW and CR, the ToA approximately doubles with the increase in the SF. For example, for range = 10 m, payload = 29 bytes, BW = 10.4 kHz , CR = 4/5, the ToA increases from 1000 ms to 1800 ms to 3400 ms as SF increases from 7, 8 and 9, respectively.

2. For a given SF, the ToA increases linearly with the increase in the CR (keeping other parameters such as range, payload and BW constant).

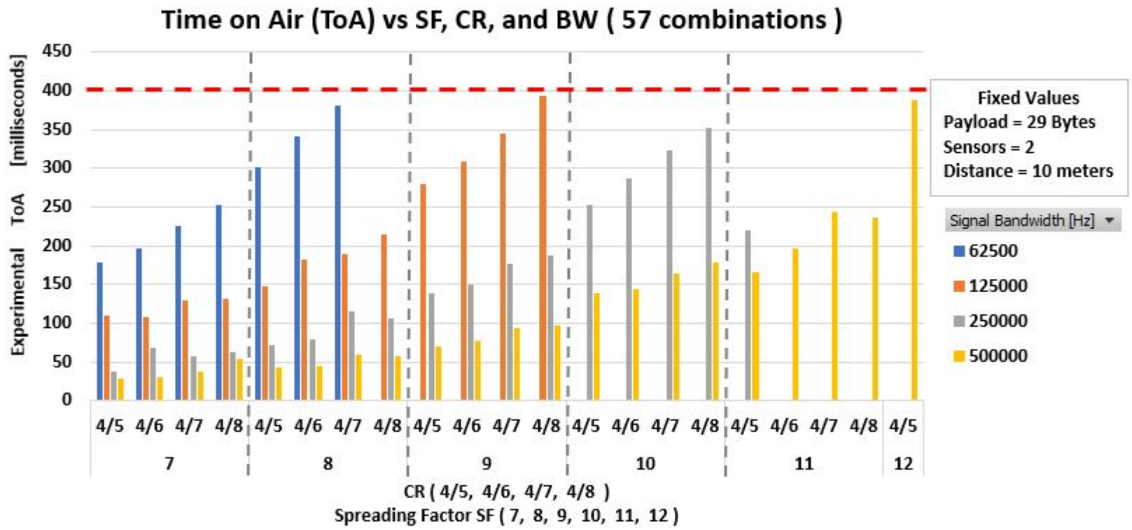


Figure 4.13: ToA vs. SF, CR, and BW (Distribution of the 57 Combinations)

3. The ToA decreases with the increase in the bandwidth, irrespective of increase in SF or CR. For every 2x increase in BW, the ToA is reduced to one half. For example, for SF = 8, CR = 4/5, the ToA decreases from 300 ms to 148 ms to 70 ms as BW increases from 62.5 kHz to 125 kHz to 250 kHz. This trend remains the same for all SF and CR.

Figure 4.14 shows the relationship between ToA and payload for different spreading factors in which the SF7 displays lowest ToA when the payload is increased. Also, it is observed that the slopes of the line for SF 11 and 12 are steeper for lower values of SF. This clearly implies that an increase in the SF will result in an increase in the communication range, however, it will cause delay in the received signal. The delay increase with the length of the payload.

The following figure illustrates the relationship between ToA and spreading factors for different coding rates. This clearly shows that for a given SF, if the CR increases, the ToA also increases. The ToA increases further with the increase in SF. This implies there is a trade-off between the data latency and robustness of the transmission channel with the increase in the CR. If we can afford latency in the data transmission, it is wise to increase the CR if there are too many interferences in the channel.

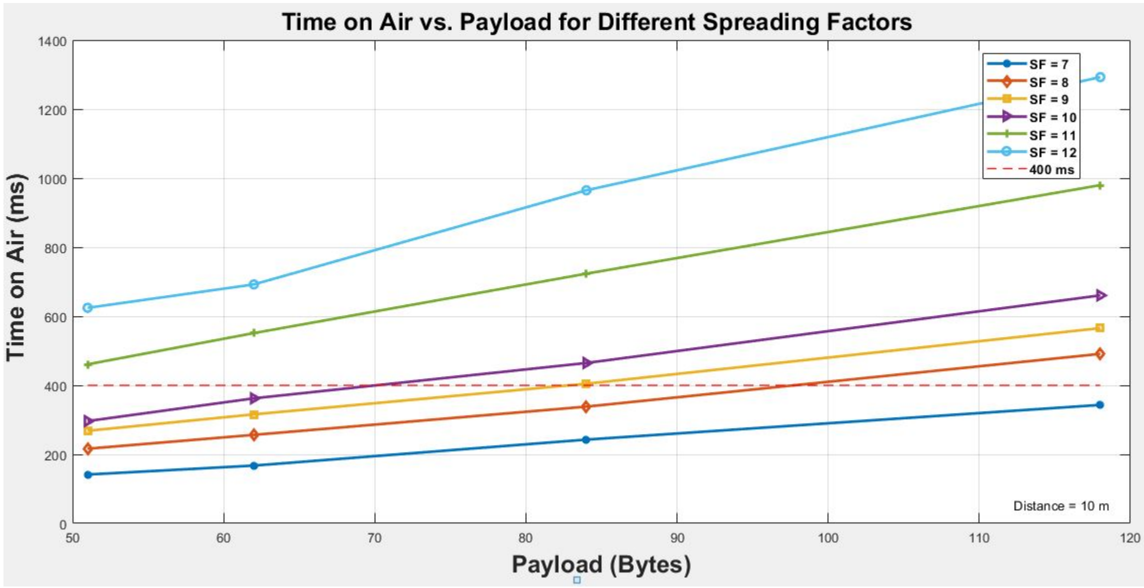


Figure 4.14: ToA vs. Payload for Different Values of SF

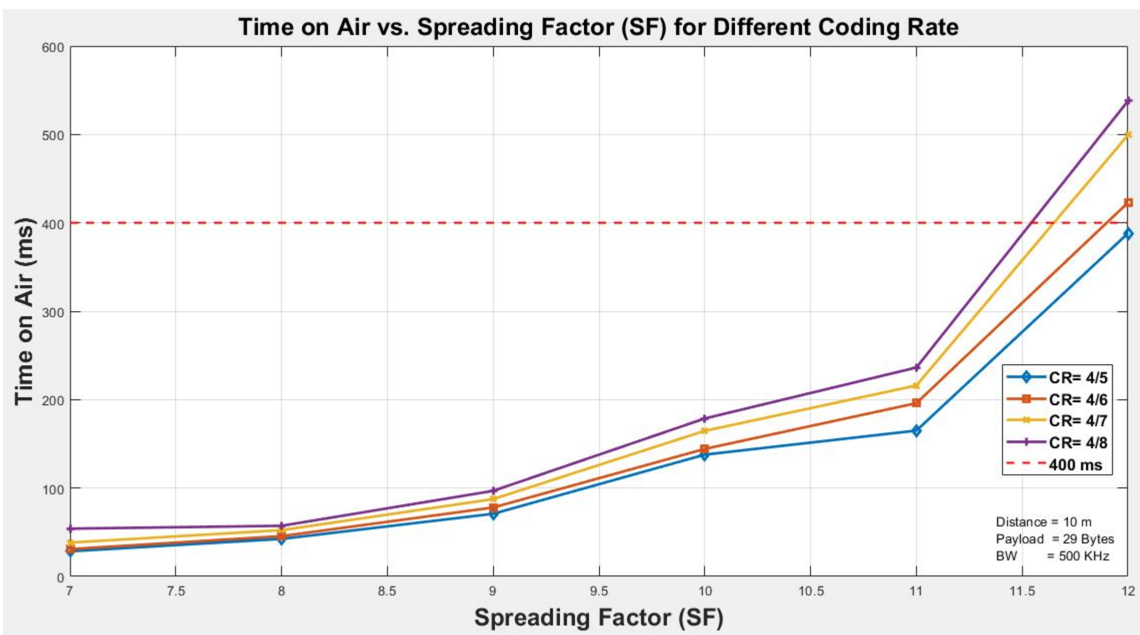


Figure 4.15: ToA vs. SF for Different Values of CR

Figure 4.16 shows the variation of ToA with SF for different values of BW. This result is for a transmission distance of 10 m and payload length of 51, 62, 84, and 118 bytes. Following observations have been made from the figure:

1. For a given payload and SF, the ToA decreases with the increase in the BW.

2. For a given BW, the ToA increases with the increase in the SF.

4. The increase in ToA is steeper for lower BWs (62.5 kHz and 125 kHz) as compare to higher BWs (250 kHz and 500 kHz) with the increase in the SF

5. FCC guidelines for ToA $<$ 400 ms is violated for BW = 62.5 kHz at SF greater than 7, for BW =125 kHz at SF greater than 8, for BW = 250 kHz at SF greater than 9 and for BW = 500 kHz at SF greater than 10.

These are important observations as it seems that working at higher BWs will result in reduced latency, however, an increase in BW also increase the noise in the channel and therefore, lowers the sensitivity of the receiver. Therefore, there is a trade-off between ToA and sensitivity of the receiver.

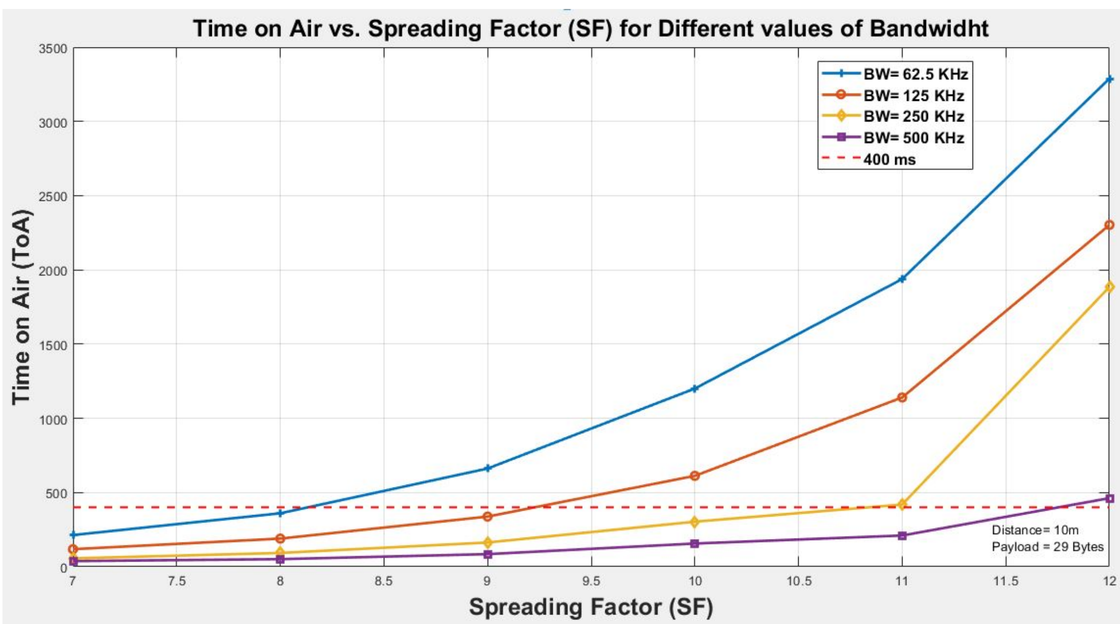


Figure 4.16: ToA vs. SF for Different Values of BW

The bit rate depends mainly on the SF and BW (Eq. 2.1); therefore, the relationship of these parameters is fundamental to define the appropriate bit rate for each application. Thus, SF = 7 with BW = 500 KHz presents the lowest ToA (28.42 ms), reaching the highest bit rate of 22 kbps for CR 4/5.

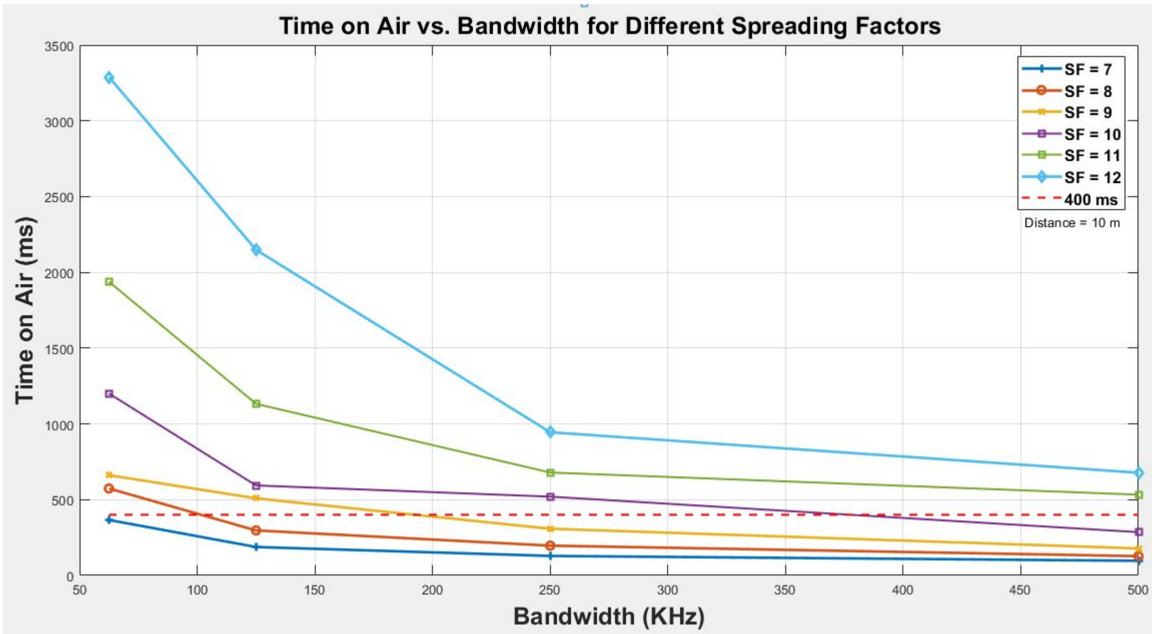


Figure 4.17: ToA vs. BW for Different Values of SF

In addition, the theoretical ToA for all 57 combinations are obtained by "LoRa Modem Calculator Tool" [50] created by Semtech (Figure 4.18). This tool calculates the ToA based on SF, BW, CR, payload, and preamble.

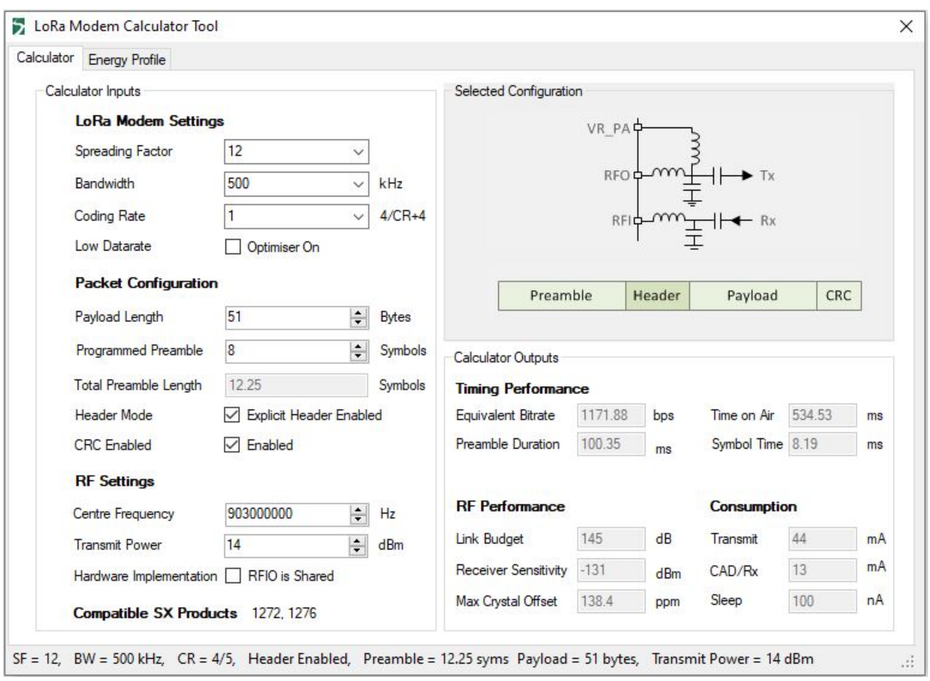


Figure 4.18: LoRa Modem Calculator Tool for ToA

In general, the experimental ToA was higher than the theoretical ToA. For SF 7, 8, and 9, the difference is approximately 60 ms, and for SF 12 the difference is 174.65 ms as shown in Figure 4.19.

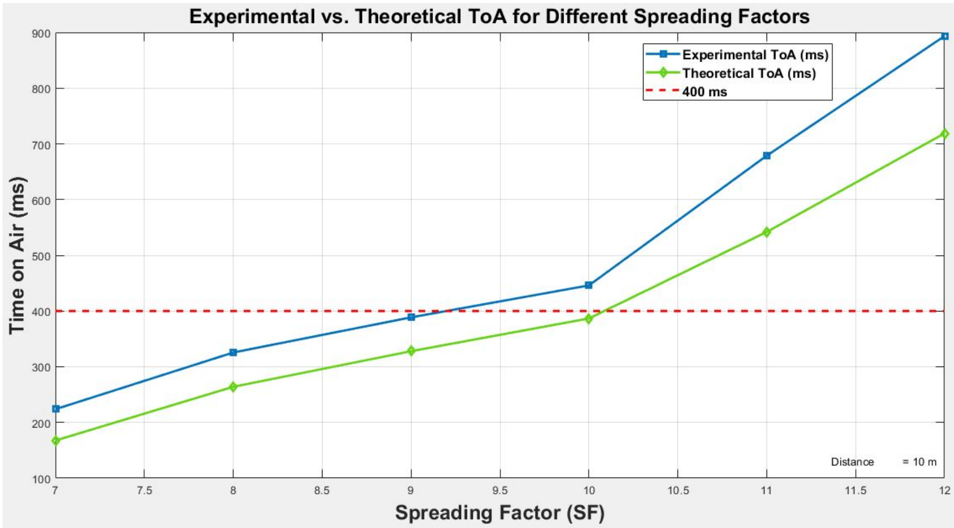


Figure 4.19: Experimental vs. Theoretical ToA for Different Values of SF

Similarly, the difference between experimental and theoretical ToA was observed for different values of BW. It was noticed that the difference value increases with the increase in the BW. For example, the time difference goes from 51 ms with BW = 62.5 KHz to 82 ms with BW = 500 KHz.

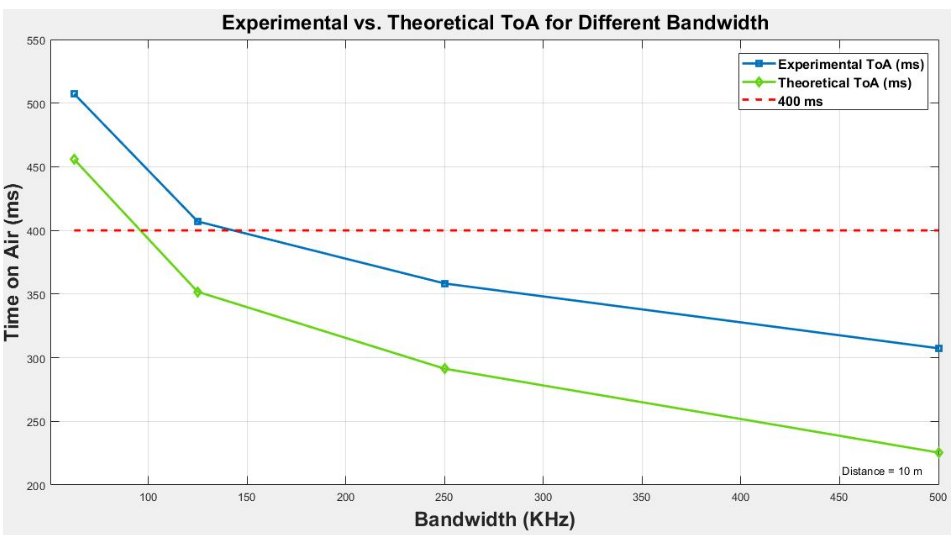


Figure 4.20: Experimental vs. Theoretical ToA for Different Values of BW

When the payload increases, it is observed that the difference between experimental and theoretical

ToA increases progressively. For instance, the time difference goes from 29 ms with payload = 51 Bytes to 124.52 ms with payload = 118 Bytes.

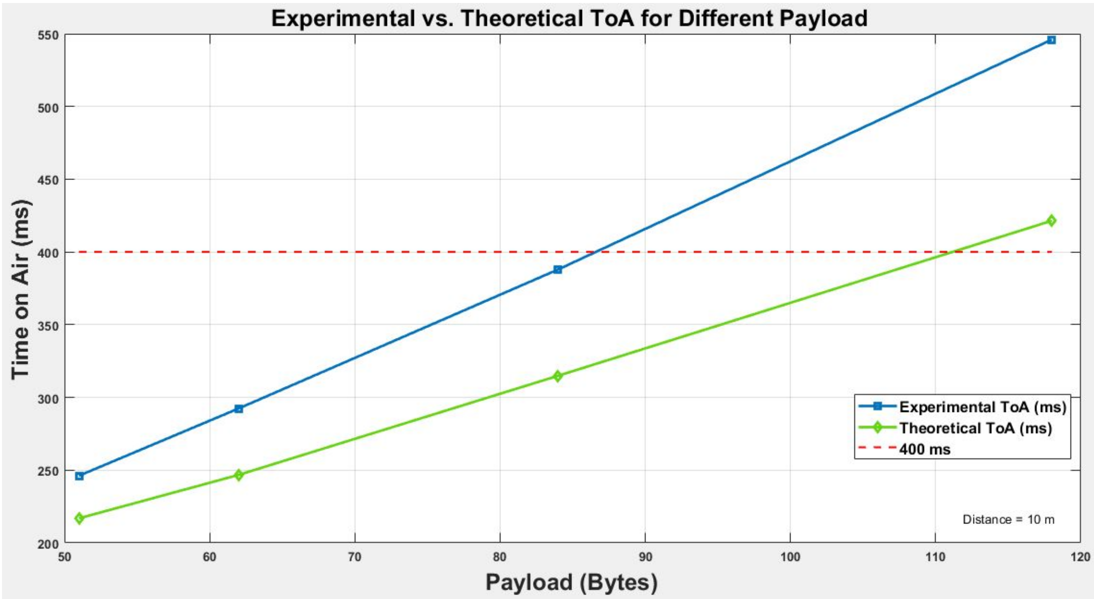


Figure 4.21: Experimental vs. Theoretical ToA for Different Values Payload

Also, an Independent T-Test is carried out between the experimental and theoretical values to determine the significant difference between these values. The Hypothesis was "experimental ToA value is more delayed than theoretical ToA," Therefore it was numerically obtained that the delay value of experimental ToA (***M*** = 368.13, ***SD*** = 248.46, ***n*** = 228) was hypothesized to be greater than the delay value of theoretical ToA (***M*** = 300, ***SD*** = 221.04, ***n*** = 228). This difference was significant, ***t*** (454) = 3.09, ***p*** = 0.001051 (1 tail).

Table 4.2: ***t***-Test: Two-Sample Assuming Equal Variances

Description	Experimental ToA [ms]	Theoretical ToA [ms]
Mean	368.13	300.00
Median	303.91	240
Standard Deviation	248.46	221.04
Range	1305.94	1041.35
Minimum	44.77	25.66
Maximum	1350.71	1067.01
Variance	61732.21	48858.20
Observations	228	228
Pooled Variance	55295.20	
Hypothesized Mean Difference	0	
df (degrees of freedom)	454	
t Stat	3.09323383947197	
P(T $\leq$ t) one-tail	0.00105100089636558	
t Critical one-tail	1.64821684748403	
P(T $\leq$ t) two-tail	0.00210200179273117	
t Critical two-tail	1.96520297265604	

4.5 Outdoor Environment Tests

The outdoor tests were carried out using Field Test Device and Dragino LG308 LoRaWAN gateway because they both have the ***adaptive data rate*** feature. In addition, a propagation study is performed using the radio planning tool "CloudRF," which uses accurate terrain elevation data and propagation models such as Okumura-Hata.

4.5.1 Adaptive Data Rate Feature Test

The gateway used a waterproof external 915 MHz Omni-directional antenna which was 18 feet high above ground level (AGL). The transmission power used for outdoor experimentation was 20 dBm or 0.1 W.

The main objective of the outdoor experimentation was to analyze the sensitivity of the LoRa device in terms of ***received signal strength indicator*** and ***signal to noise ratio***values. Multiple packets were sent from the sensor nodes to the LoRa gateway and the RSSI values were observed using FTD which was located in the moving end terminal. All packets were sent using BW= 125 KHz and CR= 4/5. Therefore, depending on the radio conditions and the history of the 20 up-link messages received, the ADR is managed by the network serve (NS) which optimizes the transmission parameters to perform the fastest possible data rate.

Figure 4.22: The LoRa Testbed Showing Gateway (left) and FTD (right) using the "Google Earth"

The Dragino LG308 gateway allows the variation of spreading factors from 7 to 10. The maximum distance at which the signal was lost between FTD and the gateway was up to 1.5 km with SF= 8, RSSI= -119 dBm, and SNR= -10 dB. Also, the SF = 7 was maintained up to 577 meters with RSSI = -111 dBm and SNR = -5 dB. The positive SNR values were obtained when the distance between FTD and gateway was up to 400 m. Furthermore, the SF 10 was observed when radio conditions were RSSI = -125 dbm and SNR = -15 dB (Figure 4.23).

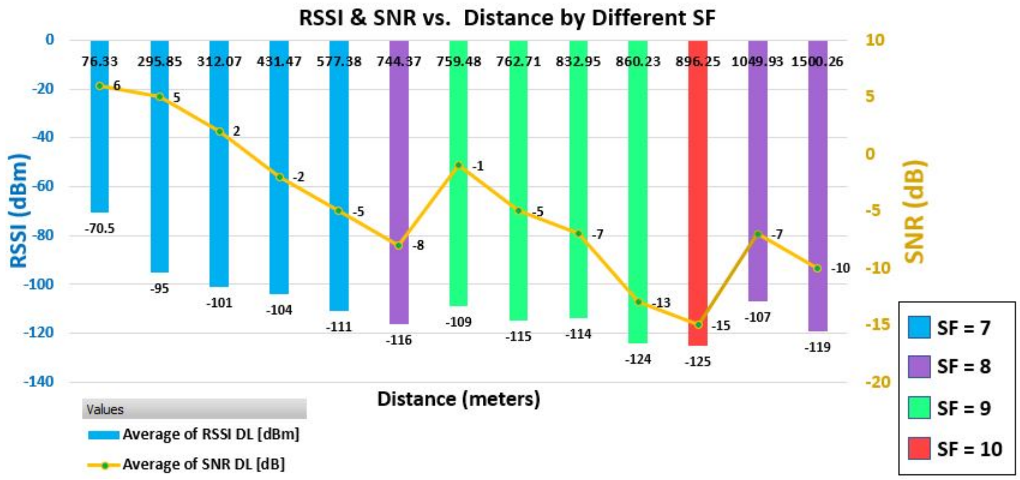


Figure 4.23: RSSI and SNR vs. Distance for Different SFs

The difference between experimental and theoretical RSSI values are presented in Table 4.3.

Table 4.3: Experimental vs. Theoretical RSSI

Location	Distance (meters)	SNR (dB)	Exp. RSSI (dBm)	The. RSSI (dBm)	SF
1	76.33	6	-70.5	-73.1	7
2	295.85	5	-95	-96.8	7
3	312.07	2	-101	-97.7	7
4	431.47	-2	-104	-103.4	7
5	577.38	-5	-111	-108.4	7
6	762.71	-5	-115	-113.3	9
7	759.48	-1	-109	-113.2	9
8	896.25	-15	-125	-116.1	10
9	744.37	-8	-116	-112.8	8
10	860.23	-13	-124	-115.4	9
11	832.95	-7	-114	-114.8	9
12	1049.93	-7	-107	-118.8	8
13	1500.26	-10	-119	-125	8

4.5.2 Propagation Study

The propagation study is performed using the radio planning tool CloudRF, which uses accurate terrain elevation and the Okumura-Hata propagation model. The location of the gateway is essential to implement LoRa communication. This location must be strategically planned to guarantee optimal levels of quality (SNR) and coverage (RSSI). It is recommended to consider all losses and gains of the system to obtain an accurate simulation. Furthermore, the simulation helps identify coverage gaps to install additional gateways, increasing system coverage, and capacity. The configurations are shown in the Table 4.4. Based on the antenna height at 18 feet and the transmit power at 20 dBm. Figure 4.24 shows healthy RSSI levels (from -52 to -80 dBm) up to approximately 600 meters. Also, the RSSI levels worsens as the distance between FTD and gateway increases beyond 1 km.

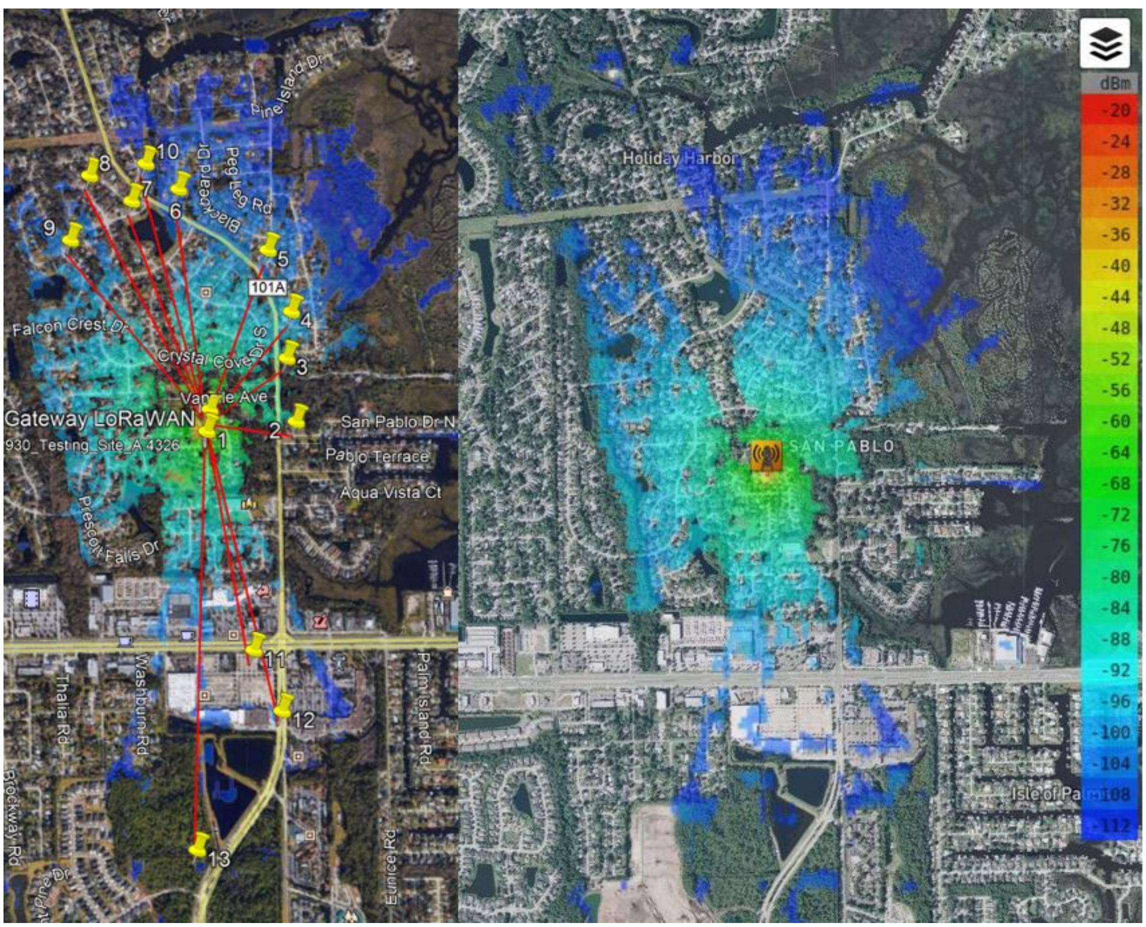


Figure 4.24: Propagation Study

Table 4.4: Cloud RF Settings

Parameter	Description	Value
Transmitter	Frequency	903.9 MHz
	RF Power	20 dBm
	Bandwidth	125 KHz
	Coordinates	Latitude and Longitude
	Height AGL	18 feed
Antenna Tx	Pattern	915 MHz OMNI
	Antenna Gain	2 dBi
	Feeder loss	0.3 dB
Receiver	Height AGL	4 feed
	Antenna Gain	1 dBi
	Sensitivity	-140 dBm
Model	Propagation model	Okumura-Hata
	Environment	Conservative / City
	Sensitivity	-140 dBm

Chapter 5
Conclusion and Future Work

5.1 Conclusion

Based on the results obtained, the planning of the physical parameters is significant for developing a low-power long distance communication via LoRa. The LoRa transmission can be optimized using the accurate radio parameters such as SF, CR, and BW, as well as the data from the sensors (payload). These parameters are essential to optimize channel usage (Time on Air), save power consumption, and resist interference. Specifically, the bit rate depends mainly on the SF and BW (Eq. 2.1); therefore, the relationship of these parameters is fundamental to define the appropriate bit rate for each application. Thus, SF = 7 with BW = 500 KHz presents the least latency in the system (minimum ToA) and reaching the highest bit rate. However, this combination is not always the best as it limits the communication range and sensitivity of the receiver.

There are various trade-offs in LoRa communication which requires compromises between ToA and BW usage. Increasing the bandwidth provides higher data rate and reduced ToA, however, it decreases the sensitivity of the receiver which leads to lower values of link budget. Also, since BW is a limited resource in engineering, it demands maximum performance using minimal resources. Therefore, a right selection of radio parameters such as SF,CR and payload would help to optimize the BW resource.

When a payload size of 25 bytes (using 2 sensors) was connected to the ThingSpeak server, only 57 out of 120 configurations met the FCC's requirement on ToA (< 400 ms). It was observed that the number of configurations reduced further to 23, when the payload size was increased up to 118 bytes (using 10 sensors). These configurations comprise of SF = 7, 8 and 9 with 500 MHz BW (in most of the cases). Therefore, the LoRa messages can be optimized using the appropriate payload size. From results obtained in Chapter 4, it was investigated. experimentally that low values of SF are capable of handling higher payload size. Please refer to the Table 4.1 which is based on results from Chapter 4. This will result in lower energy consumption and increased battery life.

In addition, the ADR feature is recommended for the static sensor because the network server uses the history of the last 20 up-link messages received with radio conditions. In contrast, the ADR is not recommended for mobile sensors because the attenuation and radio conditions can change rapidly.

The results of experimental ToA were greater than the results of theoretical ToA for most tests. Consequently, the independent T-Test was performed between these results. In other words, there is a statistically significant difference between the experimental and theoretical results. Therefore, the results show that the difference between the experimental and theoretical results is significant by $t\ (454) = 3.09$, $p = 0.001051$ (1 tail).

5.2 Future Work

The development of wireless sensors via LoRa (long-range coverage) allows users to make preventative and reactive decisions. For example, the flame sensor makes it possible to react to a potential fire and save lives. The research work presented in this thesis showed that LoRa communication is an effective and powerful solution to offer advantages such as long-range coverage connectivity with low power consumption, an unlicensed spectrum, and affordability. Therefore, LoRa communication can be applied in various fields and integrated systems, for example, into fire evacuation system projects.

The fire evacuation systems allow the occupants of a building to determine the best evacuation route when the building is on fire from a possible fire. By installing CO/CO_2 and flame sensors in each room of the building, it is possible to know the exact location of the fire and its real-time spreading dynamics. LoRa sensors are responsible for sending information such as temperature, humidity, CO_2, number of occupants, etc. All this information must be processed and analyzed by an integration platform. The "IoT in a BoX from My Devices" server shows the location of the sensors in the building design (Figure 5.1) and has various integration platforms such as: Webhook, Amadeus HoTSOS, ARM Treasure Data, AWS Kinesis, AWS S3, AWS SQS, Azure Event Hubs, Azure IoT Central, Azure IoT Hub, Azure Service bus, Azure Storage, Discord Webhook, Google BigQuery, etc.

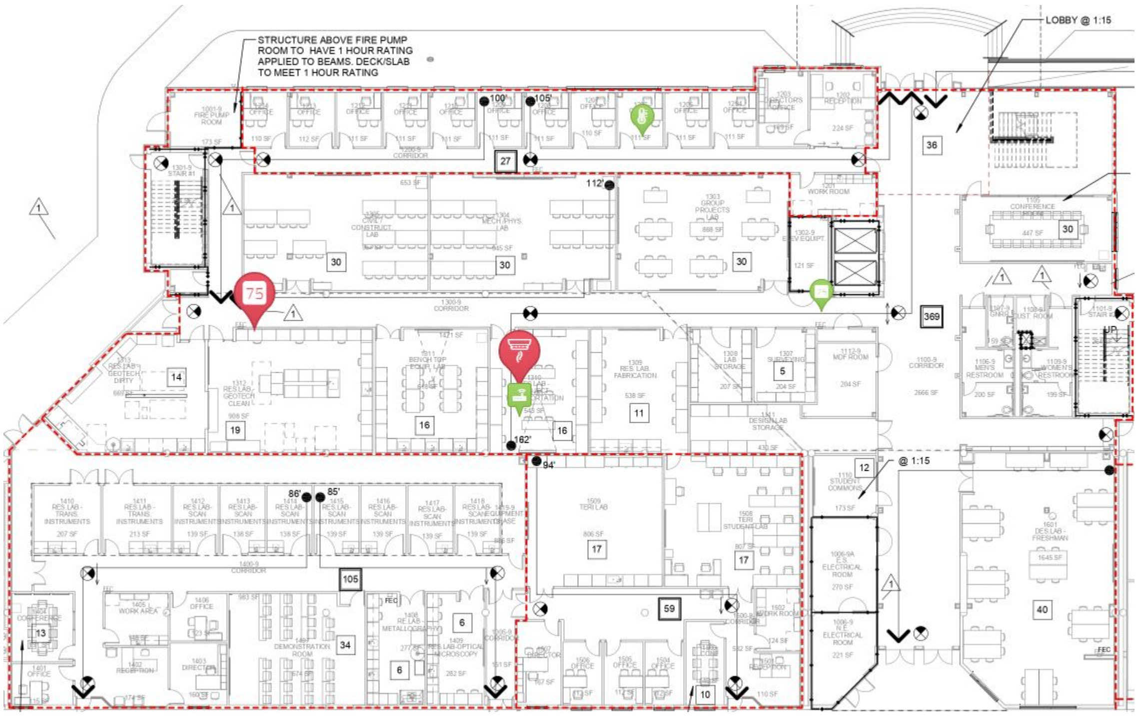


Figure 5.1: First Floor Building 4 at University of North Florida

Additionally, it is recommended to evaluate the optimal placement of sensors in order to maximize the coverage using minimum number of sensors. It is suggested to use five-ways flame sensors as they have a coverage of 120 degrees in one direction (Figure 5.3).

It is therefore concluded that LoRa technology has a great potential for low-power long distance communication. The experimental study carried out in this thesis clearly demonstrate the potential of LoRa for both indoor and outdoor applications. However, there are many trade-offs with LoRa technology which has to be taken into consideration when using this technology for a specific application. More research is required to further investigate the reliability and scalability of LoRa for its optimum performance in both indoor and outdoor applications.

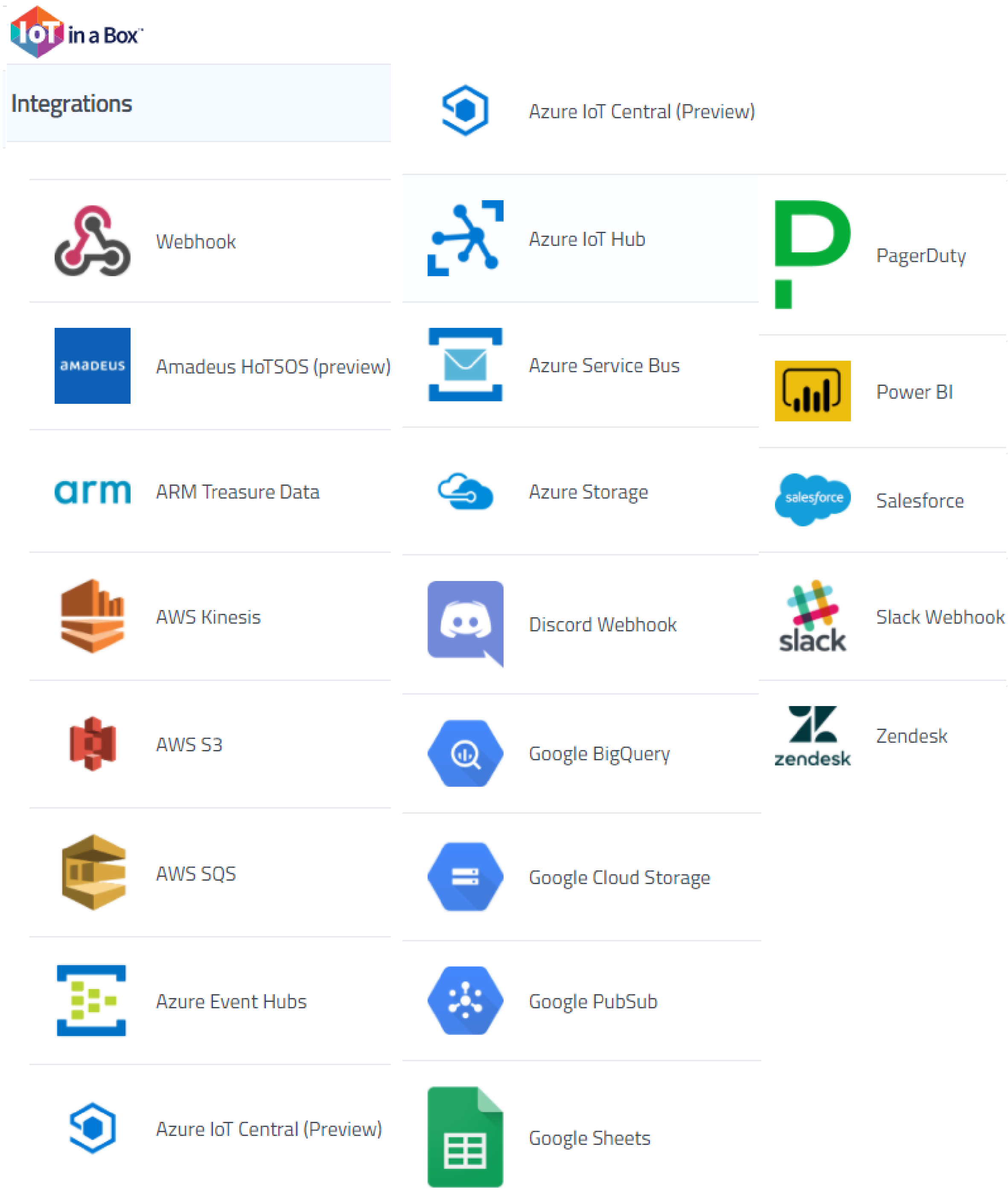


Figure 5.2: Integration Platforms on IoT in a BoX from My Devices

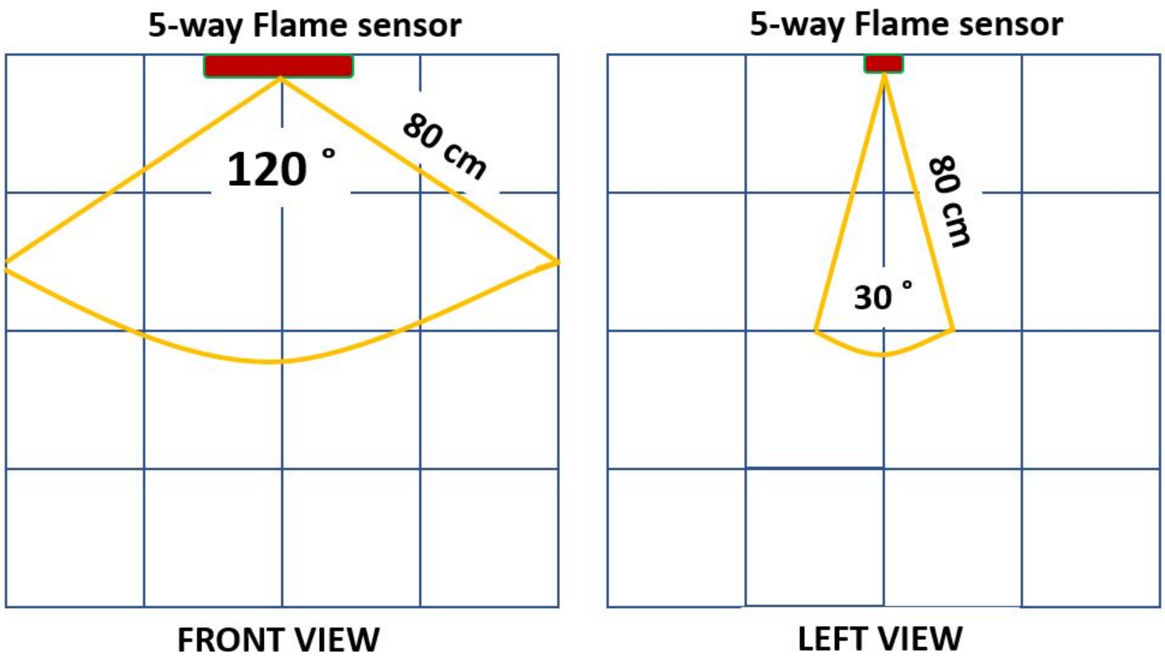


Figure 5.3: 5-way Flame Sensor Coverage Angles

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VITA

Victor Hugo Lopez Chalacan

Education

- University of North Florida - UNF — Jacksonville, Florida
  MS. in Electrical Engineering — Dec. 2020

- The University of the Armed Forces – ESPE — Quito, Ecuador
  MB. in Strategic Management and Planning — Apr. 2015

- Army Polytechnic School – ESPE — Quito, Ecuador
  BS in Electronics and Telecommunications Engineering — Jan. 2012

Professional Experience

- Radio Frequency Engineer — Jun.2020 – Aug. 2020
  ACD Telecom — Lake Mary, Florida

- Graduate Student Researcher — May.2020 – Dec. 2020
  University of North Florida (UNF) — Jacksonville, Florida

- Senior Radio Frequency Engineer — Dec. 2014 – June. 2017
  Telefonica — Quito, Ecuador

- Radio Frequency Engineer — Jan. 2012 – July. 2014
  Huawei Technologies — Quito, Ecuador

Awards

- Most Innovative Project / Research — Dec. 2019
  School of Computing Symposium at UNF — Jacksonville, Florida

APPENDIX

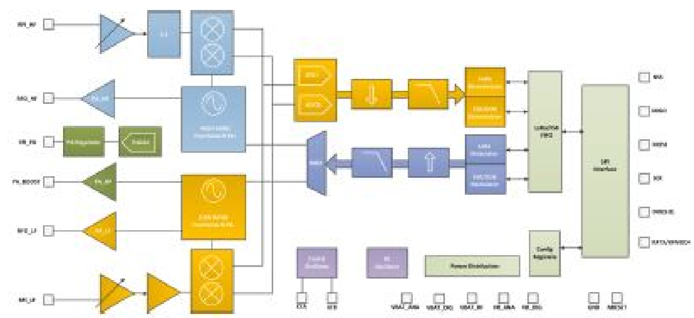
Appendix A: Data Sheet of SX1276 LoRa Transceiver

SEMTECH

SX1276/77/78/79

WIRELESS & SENSING PRODUCTS **DATASHEET**

SX1276/77/78/79 - 137 MHz to 1020 MHz Low Power Long Range Transceiver



GENERAL DESCRIPTION

The SX1276/77/78/79 transceivers feature the LoRa® long range modem that provides ultra-long range spread spectrum communication and high interference immunity whilst minimising current consumption.

Using Semtech's patented LoRa modulation technique SX1276/77/78/79 can achieve a sensitivity of over -148dBm using a low cost crystal and bill of materials. The high sensitivity combined with the integrated +20 dBm power amplifier yields industry leading link budget making it optimal for any application requiring range or robustness. LoRa provides significant advantages in both blocking and selectivity over conventional modulation techniques, solving the traditional design compromise between range, interference immunity and energy consumption.

These devices also support high performance (G)FSK modes for systems including WMBus, IEEE802.15.4g. The SX1276/77/78/79 deliver exceptional phase noise, selectivity, receiver linearity and IIP3 for significantly lower current consumption than competing devices.

ORDERING INFORMATION

Part Number	Delivery	MOQ / Multiple
SX1276IMLTRT	T&R	3000 pieces
SX1277IMLTRT	T&R	3000 pieces
SX1278IMLTRT	T&R	3000 pieces
SX1279IMLTRT	T&R	3000 pieces
SX1276WS[1]	Wafer Form	1 Wafer (2000 dies)

1. For Wafer deliveries, refer to the corresponding "Wafer Delivery Specification"

- QFN 28 Package - Operating Range [-40;+85°C]
- Pb-free, Halogen free, RoHS/WEEE compliant product

KEY PRODUCT FEATURES

- LoRa® Modem
- 168 dB maximum link budget
- +20 dBm - 100 mW constant RF output vs. V supply
- +14 dBm high efficiency PA
- Programmable bit rate up to 300 kbps
- High sensitivity: down to -148 dBm
- Bullet-proof front end: IIP3 = -11 dBm
- Excellent blocking immunity
- Low RX current of 9.9 mA, 200 nA register retention
- Fully integrated synthesizer with a resolution of 61 Hz
- FSK, GFSK, MSK, GMSK, LoRa® and OOK modulation
- Built-in bit synchronizer for clock recovery
- Preamble detection
- 127 dB Dynamic Range RSSI
- Automatic RF Sense and CAD with ultra-fast AFC
- Packet engine up to 256 bytes with CRC
- Built-in temperature sensor and low battery indicator

APPLICATIONS

- Automated Meter Reading.
- Home and Building Automation.
- Wireless Alarm and Security Systems.
- Industrial Monitoring and Control
- Long range Irrigation Systems

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Appendix B: Data Sheet of Dragino LG01-N Single Channel LoRa Gateway

Single Channel LoRa Gateway

LG01N / OLG01N

Single Channel LoRa Gateway Indoor & Outdoor version

OVERVIEW:

LG01N & OLG01N are open source single channel LoRa Gateway. It lets you bridge LoRa wireless network to an IP network via WiFi, Ethernet, 3G or 4G cellular. The LoRa wireless allows users to send data and reach extremely long ranges at low data-rates.
It provides ultra-long range spread spectrum communication and high interference immunity.

LG01N & OLG01N has WiFi interface, Ethernet port and USB host port. These Inter -faces provide flexible methods for users to connect their sensor networks to Internet. LG01N & OLG01N can support the LoRaWAN protocol in single frequency and customized LoRa transmit protocol. LG01N and OLG01N is the upgrade version of LG01-P & LG01-S & OLG01 LoRa Gateway, the new version can support more end nodes. The aim for LG01N / OLG01N is to provide a low cost IoT wireless solution to support upto 300 sensor nodes.

Features:

- Open Source OpenWrt system
- Low power consumption
- Firmware upgrade via Web
- Software upgradable via network
- Flexible protocol to connect to IoT servers
- Auto-Provisioning
- Built-in web server
- Managed by Web GUI, SSH via LAN or WiFi
- Internet connection via LAN, WiFi, 3G or 4G
- Failsafe design provides robustly system
- 1 x SX1276/SX1278 LoRa modules
- Limited support in LoRaWAN/ Support Private LoRa protocol
- Support upto 300 nodes
- Max range in LoRa: 5~10 km. Density Area:>500m

Specifications:

Linux Side:

- Processor: 400MHz, 24K MIPS
- Flash: 16MB ; RAM: 64MB

Interfaces:

- 10M/100M RJ45 Ports x 2
- WiFi: 802.11 b/g/n
- LoRa Wireless
- Power Input: 12V DC
- USB 2.0 host connector x 1
- USB 2.0 host internal interface x 1
- 3G/4G module (optional)

Order Option:

Indoor Version:

LG01-XXX-YY.

Outdoor Version:

OLG01-XXX-YY.

-XXX:

433: For Bands: EU433, CN470
868: For Bands: EU868,IN865
915: For US915,AU915,AS923,KR920

-YY:

EC25-AU: Latin America, New Zeland, Taiwan
EC25-E: EMEA, Korea, Thailand, India
EC25-A: North America/ Rogers/AT&T/T-Mobile
EC25-J: Japan, DOCOMO/SoftBank/ KDDI

Appendix C: Data Sheet of Dragino LG308 Single Channel LoRa Gateway

Open Source LoRaWAN Gateway

LG308

• None-4G version doesn't have black 4G antenna

OVERVIEW:

The LG308 is an open source LoRaWAN Gateway. It lets you bridge LoRa wireless network to an IP network via WiFi, Ethernet, 3G or 4G cellular. The LoRa wireless allows users to send data and reach extremely long ranges at low data-rates.

The LG308 is use semtech packet forwarder and fully compatible with LoRaWAN protocol. It includes a SX1301 LoRa concentrator, which provide 10 programmable parallel demodulation paths.

LG308 has pre-configured standard LoRaWAN frequency bands to use for different countries. User can also customized the frequency bands to use in their own LoRa network.

LG308 has optional built-in LoRaWAN server. System integrator can use it to integrate with their existing IoT Service without set up own LoRaWAN server or use 3rd party LoRaWAN service.

Features:

- Open Source OpenWrt system
- Managed by Web GUI, SSH via LAN or WiFi
- LoRaWAN Gateway
- Emulates 49x LoRa demodulators
- Built-In LoRaWAN server
- 10 programmable parallel demodulation paths

Applications:

- Smart Buildings & Home Automation
- Logistics and Supply Chain Management
- Smart Metering
- Smart Agriculture
- Smart Cities
- Smart Factory

Specifications:

LoRa Interfaces:

- 1 x SX1301 + 2 x 1257 LoRa Transceiver
- Max Output Power: 27dBm
- Sensitivity: -140dBm

General Interfaces:

- 10M/100M RJ45 Ports x 2
- 1 x 2.4G WiFi (802.11 bgn)
- 1 x USB host port
- 1 x Mini-PCIe Interface
- Power Input: 12v, 1A

Ordering Info:

- LG308-868 (For Band: EU868,IN865)
- LG308-868-EC25 (4G version)
- LG308-915 (For Bands: US915,AU915, AS923,KR920)
- LG308-915-EC25 (4G version)

Appendix D: Data Sheet of Field Test Device LoRaWAN 915

FIELD TEST DEVICE LoRaWAN 915

Adeunis RF
Wireless products & solutions

Highlights

- Ready-to-use device
- Range up to 25 km
- LoRaWAN V1.0 network protocol
- Class A & C
- High precision GPS
- Self-powered and rechargeable
- Dedicated web app.

LoRa Alliance

Field Test Device - Network validation, prior to your solution deployment

The **LoRaWAN Field Test Device by ADEUNIS RF** is a ready to use system, which provides connection to the any operated network using the LoRaWAN V1.0 protocol. It allows to transmit, receive and instantly view the radio frames on the used network.

Equipped with a **large LCD screen**, you can check all operating information (GPS coordinates, temperature, battery ...) and use of the network (uplink, downlink, SF, Packet Error Rate ..).
Its **ultra-fast and precise GPS**, optimises geolocation operations. .

This Field Test Device is particularly suitable for the **validation of applications** like sensor networks, asset tracking, smart buildings, metering, security, or M2M.

With **built-in rechargeable battery**, this demonstrator allows for many hours of use and can be recharge with any type of mobile phone charger.

Performances

Range : up to 25 km
Power : up to 100mW
Radiated RF power : up to 20dBm
Sensitivity : up to -140dBm
Frequencies : 902-928MHz
Modulation : LoRa™

Hardware

High precision GPS
Micro USB : batt charging & configuration
Buttton :frame transmission

Firmware

LoRaWAN V1 network protocol

Consumption & needs

Battery : 2000mAh
Autonomy: approx. 10 hours

General information

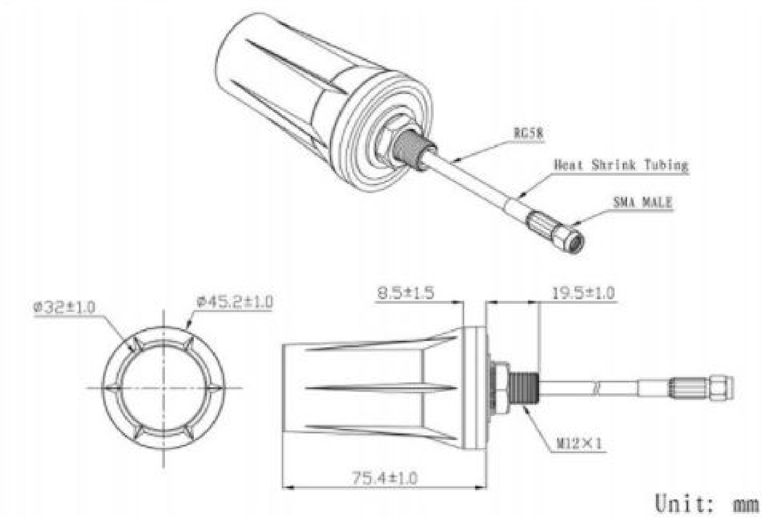
Dimensions : 180 x 72 x 21mm
Weight : 150g
Operating temperature : -20°C /+75°C

Reference

- **ARF_8124_AA** : Field Test Device LoRaWAN 915

Appendix E: Data Sheet of Ultra Long Range Waterproof LoRa Antenna Radio 915 MHz

DIMENSIONS



SPECIFICAIONS

Item		Specifications
Antenna	Frequency Range	824~960/1710~2170MHz
	Polarization	Linear
	Gain	2dBi（Zenith）
	V.S.W.R	<2.0
	Impedance	50 Ω
Mechanical	Cable	RG58 or others
	Connector	SMA or others
	Radome Material	ABS
	Mounting Method	Screw
Environmental	Operating Temperature	-40℃~+85℃
	Relative Humidity	Up to 95%
	Vibration	10 to 55Hz with 1.5mm amplitude 2hours
	Environmentally Friendly	ROHS Compliant

Appendix F: Data Sheet of DHT11 Temperature and Humidity Sensor

AOSONG

Your specialist in innovating humidity & temperature sensors

Digital relative humidity & temperature sensor DHT11

1. Feature & Application:

*Good precision
*Resistive type
*Full range temperature compensated
*Relative humidity and temperature measurement
*Calibrated digital signal
*Outstanding long-term stability
*Extra components not needed
*Long transmission distance, up to 100 meters
*Low power consumption
*4 pins packaged and fully interchangeable

2. Description:

DHT11 output calibrated digital signal. It applys exclusive digital-signal-collecting-technique and humidity sensing technology, assuring its reliability and stability. Its sensing elements is connected with 8-bit single-chip computer.

Every sensor of this model is temperature compensated and calibrated in accurate calibration chamber and the calibration-coefficient is saved in type of programme in OTP memory, when the sensor is detecting, it will cite coefficient from memory.

Small size & low consumption & long transmission distance(100m) enable DHT11 to be suited in all kinds of harsh application occasions. Single-row packaged with four pins, making the connection very convenient.

3. Technical Specification:

Model	DHT11	
Power supply	3.3-5.5V DC	
Output signal	digital signal via Aosong 1-wire bus	
Sensing element	Polymer humidity resistor	
Operating range	humidity 20-90%RH;	temperature 0~50Celsius
Accuracy	**humidity +-5%RH**;	temperature +-2Celsius
Resolution or sensitivity	humidity 1%RH;	temperature 1Celsius
Repeatability	humidity +-2%RH;	temperature +-1Celsius
Humidity hysteresis	+-1%RH	
Long-term Stability	+-1%RH/year	
Interchangeability	fully interchangeable	

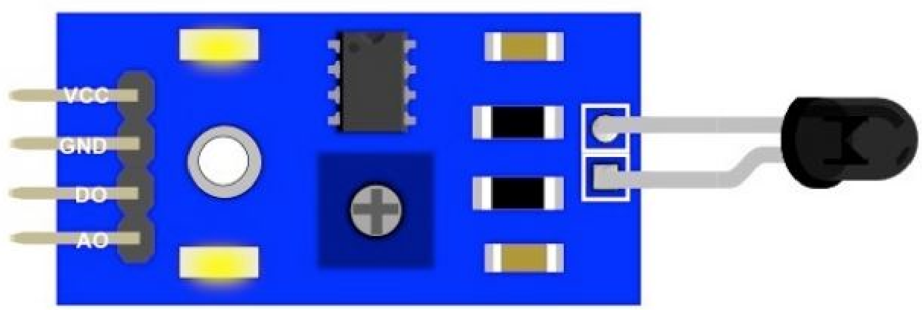
Appendix G: Data Sheet of Flame Sensor

Description

- Detects a flame or a light source of a wavelength in the range of 760nm-1100 nm
- Detection distance: 20cm (4.8V) ~ 100cm (1V)
- Detection angle about 60 degrees, it is sensitive to the flame spectrum.
- Comparator chip LM393 makes module readings stable.
- Adjustable detection range.
- Operating voltage 3.3V-5V
- Digital and Analog Output
  - DO digital switch outputs (0 and 1)
  - AO analog voltage output
- Power indicator and digital switch output indicator

Interface Description (4-wire)

1) VCC -- 3.3V-5V voltage
2) GND -- GND
3) DO -- board digital output interface (0 and 1)
4) AO -- board analog output interface



Future Electronics Egypt Ltd. (Arduino Egypt).

Appendix H: Code 1/4 Arduino TTN with Cayenne Integration

```
/***2015 Thomas Telkamp and Matthijs Kooijma* ermission is hereby granted, free of charge, to any
#include <lmic.h>
#include <hal/hal.h>
#include <SPI.h>
#include <dht.h> //(DHT11 Temperaure and Humidity Library - VICTOR LOPEZ)
dht DHT;
#define DHT11_PIN 5 //( define input pin Digital 5 - VICTOR LOPEZ)
const int flame_pin=3;  //define the input pin of flame sensor (PIN 3 DIGITAL - VICTOR LOPEZ)
int Flame = HIGH;  //  (define Flame - VICTOR LOPEZ)
const int ctl_pin=4; //define the output pin of realy
static float temperature,humidity,tem,hum;
static uint8_t LPP_data[13] = {0x01,0x67,0x00,0x00,0x02,0x68,0x00,0x03,0x01,0x00,0x04,0x00,0x00};
static uint8_t opencml[4]={0x03,0x00,0x64,0xFF},closecml[4]={0x03,0x00,0x00,0xFF}; //the payload o
static unsigned int count = 1;
#ifdef COMPILE_REGRESSION_TEST
# define FILLMEIN 0
#else
# define FILLMEIN (#dont edit this, edit the lines that use FILLMEIN)
#endif
// LoRaWAN NwkSKey, network session key from TTN
    static const PROGMEM u1_t NWKSKEY[16] = { 0x81, 0x97, 0x24, 0x74, 0xDF, 0x34, 0x2A, 0xBF, 0xA8
// LoRaWAN AppSKey, application session key from TTN
    static const u1_t PROGMEM APPSKEY[16] = { 0xA1, 0xC6, 0xBC, 0x6A, 0x8A, 0xD4, 0x59, 0x5B, 0x3A
// LoRaWAN end-device address (DevAddr) from TTN
    static const u4_t DEVADDR = 0x26021965;
    void os_getArtEui (u1_t* buf) { }
    void os_getDevEui (u1_t* buf) { }
    void os_getDevKey (u1_t* buf) { }
    static uint8_t mydata[6];
    static osjob_t sendjob;
    const unsigned TX_INTERVAL = 15; // Schedule TX every this many seconds (might become longer d
    const lmic_pinmap lmic_pins = {  // Pin mapping // TL Modifications: // Specifically for Ardui
    .nss = 10,
    .rxtx = LMIC_UNUSED_PIN,
    .rst = 9,
    .dio = {2, 6, 7},
    };
void onEvent (ev_t ev) {
    Serial.print(os_getTime());
    Serial.print(": ");
    switch(ev) {
        case EV_SCAN_TIMEOUT:
            Serial.println(F("EV_SCAN_TIMEOUT"));
            break;
        case EV_BEACON_FOUND:
            Serial.println(F("EV_BEACON_FOUND"));
            break;
        case EV_BEACON_MISSED:
            Serial.println(F("EV_BEACON_MISSED"));
            break;
```

Appendix H: Code 2/4 Arduino TTN with Cayenne Integration

```
        case EV_BEACON_TRACKED:
            Serial.println(F("EV_BEACON_TRACKED"));
            break;
        case EV_JOINING:
            Serial.println(F("EV_JOINING"));
            break;
        case EV_JOINED:
            Serial.println(F("EV_JOINED"));
            break;
        case EV_JOIN_FAILED:
            Serial.println(F("EV_JOIN_FAILED"));
            break;
        case EV_REJOIN_FAILED:
            Serial.println(F("EV_REJOIN_FAILED"));
            break;
        case EV_TXCOMPLETE:
            Serial.println(F("EV_TXCOMPLETE (includes waiting for RX windows)"));
            if (LMIC.txrxFlags & TXRX_ACK)
              Serial.println(F("Received ack"));
            if (LMIC.dataLen) {
              Serial.println(F("Received "));
              Serial.println(LMIC.dataLen);
              Serial.println(F(" bytes of payload"));
            }      // Schedule next transmission
            os_setTimedCallback(&sendjob, os_getTime()+sec2osticks(TX_INTERVAL), do_send);
            break;
        case EV_LOST_TSYNC:
            Serial.println(F("EV_LOST_TSYNC"));
            break;
        case EV_RESET:
            Serial.println(F("EV_RESET"));
            break;
        case EV_RXCOMPLETE:
            Serial.println(F("EV_RXCOMPLETE")); // data received in ping slot
            break;
        case EV_LINK_DEAD:
            Serial.println(F("EV_LINK_DEAD"));
            break;
        case EV_LINK_ALIVE:
            Serial.println(F("EV_LINK_ALIVE"));
            break;
        case EV_TXSTART:
            Serial.println(F("EV_TXSTART"));
            break;
        default:
            Serial.print(F("Unknown event: "));
            Serial.println((unsigned) ev);
            break;
    }
}
```

Appendix H: Code 3/4 Arduino TTN with Cayenne Integration

```
void do_send(osjob_t* j){
    if (LMIC.opmode & OP_TXRXPEND) {    // Check if there is not a current TX/RX job running
        Serial.println(F("OP_TXRXPEND, not sending"));
    } else {
        dhtTem();    // Prepare upstream data transmission at the next possible time.
        pinread();   // Prepare upstream data transmission at the next possible time.
        LMIC_setTxData2(1,LPP_data, sizeof(LPP_data), 0); // This command sends the Data
        Serial.println(F("Packet queued"));
        Serial.println(F("Packet queued"));
        Serial.print(F("Sending packet on frequency [Hz]: "));
        Serial.println(LMIC.freq);
    }
}
void setup() {
    while (!Serial); // wait for Serial to be initialized
    Serial.begin(115200);
    delay(100);     // per sample code on RF_95 test
    Serial.println(F("Starting"));
    #ifdef VCC_ENABLE
    pinMode(VCC_ENABLE, OUTPUT);
    digitalWrite(VCC_ENABLE, HIGH);
    delay(1000);
    #endif
    os_init();     // LMIC init
    LMIC_reset();  // Reset the MAC state. Session and pending data transfers will be discarded.
    #ifdef PROGMEM
    uint8_t appskey[sizeof(APPSKEY)];
    uint8_t nwkskey[sizeof(NWKSKEY)];
    memcpy_P(appskey, APPSKEY, sizeof(APPSKEY));
    memcpy_P(nwkskey, NWKSKEY, sizeof(NWKSKEY));
    LMIC_setSession (0x13, DEVADDR, nwkskey, appskey);
    #else
    LMIC_setSession (0x13, DEVADDR, NWKSKEY, APPSKEY);
    #endif
    for (int c = 0; c < 72; c++){   // disable all 72 channels used by TTN
      LMIC_disableChannel(c);
    }
    LMIC_enableChannel(8);  // (Channel 8 Freq = 903900000 - VICTOR LOPEZ)
    LMIC_setLinkCheckMode(0);
    LMIC.dn2Dr = DR_SF9;      // TTN uses SF9 for its RX2 window.
    LMIC_setDrTxpow(DR_SF7,14); // Set data rate and transmit power for uplink (note: txpow seems
    do_send(&sendjob);         // Start job
}
void dhtTem()
{
       int16_t tem_LPP;
       temperature = DHT.read11(DHT11_PIN);    //Read Tmperature data
       tem = DHT.temperature*1.0;
       humidity = DHT.read11(DHT11_PIN);      //Read humidity data
       hum = DHT.humidity* 1.0;
```

Appendix H: Code 4/4 Arduino TTN with Cayenne Integration

```
        Serial.print("###########     ");
        Serial.print("COUNT=");
        Serial.print(count);
        Serial.println("     ###########");
        Serial.println(F("The temperature and humidity:"));
        Serial.print("[");
        Serial.print(tem);
        Serial.print("℃");
        Serial.print(",");
        Serial.print(hum);
        Serial.print("%");
        Serial.print("]");
        Serial.println("");
        Serial.println("Fire?: No = 1;  YES = 0 "); // (Flame Sensor - VICTOR LOPEZ)
        Flame = digitalRead(flame_pin);
        Serial.println(Flame);
        count++;
        tem_LPP=tem * 10;
        LPP_data[2] = tem_LPP>>8;
        LPP_data[3] = tem_LPP;
        LPP_data[6] = hum * 2;
}
void pinread()
{
    int val,val1;
    val=digitalRead(ctl_pin);
    val1=digitalRead(flame_pin);
    if(val==1)
     {
        LPP_data[9]=0x01;
     }
    else
    {
        LPP_data[9]=0x00;
    }
    if(val1==1)
    {
      LPP_data[12]=0x01;    // original
          }
    else
    {
      LPP_data[12]=0x00;    //original
    }
}
void loop() {
    unsigned long now;
    now = millis();
    if ((now & 512) != 0) {
      digitalWrite(13, HIGH);
    }
    else {
      digitalWrite(13, LOW);
    }
    os_runloop_once();
    }
```

Appendix I: Code 1/3 Arduino ThingSpeak

```
#include <dht.h>
#include <SPI.h>
#include <LoRa.h>
dht DHT;
#define DHT11_PIN A0
const int flame_pin=3;  //define the input pin of flame sensor
const int buzzerPin = 8;
int Flame = HIGH;
int redled = 5;
int greenled = 6;
float temperature,humidity,tem,hum;
char tem_1[8]={"\0"},hum_1[8]={"\0"},victor_fire_1[8]={"\0"};   //(VICTOR LOPEZ)
char *node_id = "<5678>";  //From LG01 via web Local Channel settings on MQTT.//Local Channel ID(
uint8_t datasend[48];   // Payload  //(VICTOR LOPEZ)
unsigned int count = 1;
unsigned long new_time,old_time=0;
void setup()
{
      pinMode(buzzerPin, OUTPUT);
      pinMode(redled, OUTPUT);
      pinMode(greenled, OUTPUT);
      pinMode(flame_pin, INPUT);
      Serial.begin(9600);
      while (!Serial);
      Serial.println(F("Start MQTT Example of the ThingSpeak"));
      // Frequency Up-link
      if (!LoRa.begin(903900000))
      {
          Serial.println("Starting LoRa failed!");
          while (1);
      }
      // Setup Spreading Factor (6 ~ 12)
      LoRa.setSpreadingFactor(7);  // SPREADING FACTOR SF - (valor por defecto 7)
      // Setup BandWidth, option: 7800,10400,15600,20800,31250,41700,62500,125000,250000,500000
      LoRa.setSignalBandwidth(500000);   // SIGNAL BANDWIDTH - (valor por defecto 125000)
      // Setup Coding Rate:5(4/5),6(4/6),7(4/7),8(4/8)
      LoRa.setCodingRate4(5);  // CODING RATE -  (valor por defecto 5 )
      LoRa.setSyncWord(0x34);
      Serial.println("LoRa init succeeded.");
      pinMode(flame_pin,INPUT);
      attachInterrupt(1,fire,FALLING);
      LoRa.onReceive(onReceive);
      LoRa.receive();
}
void dhtTem()
{
       temperature = DHT.read11(DHT11_PIN);    //Read Tmperature data
       tem = DHT.temperature*1.0;
       humidity = DHT.read11(DHT11_PIN);      //Read humidity data
       hum = DHT.humidity* 1.0;
```

Appendix I: Code 2/3 Arduino ThingSpeak

```
        Serial.println(F("The temperature and humidity:"));
        Serial.print("[");
        Serial.print(tem);
        Serial.print("℃");
        Serial.print(",");
        Serial.print(hum);
        Serial.print("%");
        Serial.print("]");
        Serial.println("");
        Flame = digitalRead(flame_pin);
        Serial.println(Flame);
}
void dhtWrite()
{
    char data[50] = "\0";
    for(int i = 0; i < 50; i++)
    {
       data[i] = node_id[i];
    }
    dtostrf(tem,0,1,tem_1);
    dtostrf(hum,0,1,hum_1);
    dtostrf(Flame,0,1,victor_fire_1);  //(VICTOR LOPEZ)
     strcat(data,"field1=");
     strcat(data,tem_1);
     strcat(data,"&field2=");
     strcat(data,hum_1);
     strcat(data,"&field3=");     //(VICTOR LOPEZ)
     strcat(data,victor_fire_1);  //(VICTOR LOPEZ)
     strcpy((char *)datasend,data);   //PACKAGE SEND
     Serial.println((char *)datasend);
     Serial.println(sizeof datasend);
}
void fire()  // Interrupt
{
     Serial.println("Have fire,the temperature is send");
     dhtTem();
     dhtWrite();
     LoRa.beginPacket();
     LoRa.print((char *)datasend);
     LoRa.endPacket();
}
void SendData()
{
     LoRa.beginPacket();
     LoRa.print((char *)datasend);
     LoRa.endPacket();
     Serial.println("Packet Sent");
}
```

Appendix I: Code 3/3 Arduino ThingSpeak

```
void loop()
{
    new_time=millis();
    if (new_time - old_time >= 60000 || old_time == 0)    //  TIME
    {
      old_time = new_time;
      Serial.print("###########    ");
      Serial.print("COUNT=");
      Serial.print(count);
      Serial.println("    ###########");
      count++;
      dhtTem();
      dhtWrite();
      SendData();
      LoRa.receive();
    }
     Flame = digitalRead(flame_pin); //(VICTOR LOPEZ)
  if (Flame== LOW)
  {
    digitalWrite(buzzerPin, HIGH);
    digitalWrite(redled, HIGH);
    digitalWrite(greenled, LOW);
  }
  else
  {
    digitalWrite(buzzerPin, LOW);
    digitalWrite(greenled, HIGH);
    digitalWrite(redled, LOW);
  }
}
void onReceive(int packetSize) {
  // received a packet
  Serial.print("Received packet : ");
  // read packet
  for (int i = 0; i < packetSize; i++) {
      Serial.print((char)LoRa.read());
  }
  Serial.print("\n\r");
}
```

Appendix J: 120 Combinations ToA [ms] Experimental Results 1/4

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	Experimental ToA [s]	Experimental ToA [ms]
1	10	2	29	7	4/5	10400	1.0062908	1006.2908
2	10	2	29	7	4/5	62500	0.178084	178.084
3	10	2	29	7	4/5	125000	0.1090652	109.0652
4	10	2	29	7	4/5	250000	0.0380796	38.0796
5	10	2	29	7	4/5	500000	0.0284202	28.4202
6	10	2	29	7	4/6	10400	1.1453692	1145.3692
7	10	2	29	7	4/6	62500	0.1965362	196.5362
8	10	2	29	7	4/6	125000	0.1081636	108.1636
9	10	2	29	7	4/6	250000	0.0675732	67.5732
10	10	2	29	7	4/6	500000	0.0309132	30.9132
11	10	2	29	7	4/7	10400	1.3012958	1301.2958
12	10	2	29	7	4/7	62500	0.2262666	226.2666
13	10	2	29	7	4/7	125000	0.1291258	129.1258
14	10	2	29	7	4/7	250000	0.0568704	56.8704
15	10	2	29	7	4/7	500000	0.0382652	38.2652
16	10	2	29	7	4/8	10400	1.436439	1436.439
17	10	2	29	7	4/8	62500	0.253262	253.262
18	10	2	29	7	4/8	125000	0.1313838	131.3838
19	10	2	29	7	4/8	250000	0.0632582	63.2582
20	10	2	29	7	4/8	500000	0.0540672	54.0672
21	10	2	29	8	4/5	10400	1.7532644	1753.2644
22	10	2	29	8	4/5	62500	0.300497	300.497
23	10	2	29	8	4/5	125000	0.147669	147.669
24	10	2	29	8	4/5	250000	0.0712464	71.2464
25	10	2	29	8	4/5	500000	0.0424776	42.4776
26	10	2	29	8	4/6	10400	No connection	No connection
27	10	2	29	8	4/6	62500	0.3415748	341.5748
28	10	2	29	8	4/6	125000	0.1821744	182.1744
29	10	2	29	8	4/6	250000	0.0786134	78.6134
30	10	2	29	8	4/6	500000	0.0455994	45.5994
31	10	2	29	8	4/7	10400	No connection	No connection
32	10	2	29	8	4/7	62500	0.3803134	380.3134
33	10	2	29	8	4/7	125000	0.1890604	189.0604
34	10	2	29	8	4/7	250000	0.115156	115.156
35	10	2	29	8	4/7	500000	0.059169	59.169

Appendix J: 120 Combinations ToA [ms] Experimental Results 2/4

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	Experimental ToA [s]	Experimental ToA [ms]
36	10	2	29	8	4/8	10400	No connection	No connection
37	10	2	29	8	4/8	62500	0.4181606	418.1606
38	10	2	29	8	4/8	125000	0.2148256	214.8256
39	10	2	29	8	4/8	250000	0.1062128	106.2128
40	10	2	29	8	4/8	500000	0.0572764	57.2764
41	10	2	29	9	4/5	10400	3.262407	3262.407
42	10	2	29	9	4/5	62500	0.5537938	553.7938
43	10	2	29	9	4/5	125000	0.278836	278.836
44	10	2	29	9	4/5	250000	0.139119	139.119
45	10	2	29	9	4/5	500000	0.0708678	70.8678
46	10	2	29	9	4/6	10400	3.680901	3680.901
47	10	2	29	9	4/6	62500	0.6251876	625.1876
48	10	2	29	9	4/6	125000	0.3083334	308.3334
49	10	2	29	9	4/6	250000	0.150207	150.207
50	10	2	29	9	4/6	500000	0.077996	77.996
51	10	2	29	9	4/7	10400	4.149917	4149.917
52	10	2	29	9	4/7	62500	0.6933106	693.3106
53	10	2	29	9	4/7	125000	0.3449912	344.9912
54	10	2	29	9	4/7	250000	0.1772468	177.2468
55	10	2	29	9	4/7	500000	0.0941504	94.1504
56	10	2	29	9	4/8	10400	4.55843	4558.43
57	10	2	29	9	4/8	62500	0.7742132	774.2132
58	10	2	29	9	4/8	125000	0.3926112	392.6112
59	10	2	29	9	4/8	250000	0.1866918	186.6918
60	10	2	29	9	4/8	500000	0.0968262	96.8262
61	10	2	29	10	4/5	10400	No connection	No connection
62	10	2	29	10	4/5	62500	1.0004124	1000.4124
63	10	2	29	10	4/5	125000	0.5017028	501.7028
64	10	2	29	10	4/5	250000	0.2532028	253.2028
65	10	2	29	10	4/5	500000	0.13781	137.81
66	10	2	29	10	4/6	10400	No connection	No connection
67	10	2	29	10	4/6	62500	1.1400018	1140.0018
68	10	2	29	10	4/6	125000	0.5750668	575.0668
69	10	2	29	10	4/6	250000	0.2869412	286.9412
70	10	2	29	10	4/6	500000	0.1442738	144.2738

Appendix J: 120 Combinations ToA [ms] Experimental Results 3/4

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	Experimental ToA [s]	Experimental ToA [ms]
70	10	2	29	10	4/6	500000	0.1442738	144.2738
71	10	2	29	10	4/7	10400	No connection	No connection
72	10	2	29	10	4/7	62500	1.266253	1266.253
73	10	2	29	10	4/7	125000	0.6310718	631.0718
74	10	2	29	10	4/7	250000	0.3226322	322.6322
75	10	2	29	10	4/7	500000	0.164676	164.676
76	10	2	29	10	4/8	10400	No connection	No connection
77	10	2	29	10	4/8	62500	1.395084	1395.084
78	10	2	29	10	4/8	125000	0.7025698	702.5698
79	10	2	29	10	4/8	250000	0.3512968	351.2968
80	10	2	29	10	4/8	500000	0.178683	178.683
81	10	2	29	11	4/5	10400	No connection	No connection
82	10	2	29	11	4/5	62500	1.6435745	1643.5745
83	10	2	29	11	4/5	125000	0.8119005	811.9005
84	10	2	29	11	4/5	250000	0.22061	220.61
85	10	2	29	11	4/5	500000	0.164983	164.983
86	10	2	29	11	4/6	10400	No connection	No connection
87	10	2	29	11	4/6	62500	1.855305	1855.305
88	10	2	29	11	4/6	125000	0.9007425	900.7425
89	10	2	29	11	4/6	250000	0.442041	442.041
90	10	2	29	11	4/6	500000	0.196	196
91	10	2	29	11	4/7	10400	No connection	No connection
92	10	2	29	11	4/7	62500	2.026975	2026.975
93	10	2	29	11	4/7	125000	1.020916	1020.916
94	10	2	29	11	4/7	250000	0.4794195	479.4195
95	10	2	29	11	4/7	500000	0.243952	243.952
96	10	2	29	11	4/8	10400	No connection	No connection
97	10	2	29	11	4/8	62500	2.2262915	2226.2915
98	10	2	29	11	4/8	125000	1.0805455	1080.5455
99	10	2	29	11	4/8	250000	0.533692	533.692
100	10	2	29	11	4/8	500000	0.236316	236.316
101	10	2	29	12	4/5	10400	No connection	No connection
102	10	2	29	12	4/5	62500	3.2885115	3288.5115
103	10	2	29	12	4/5	125000	1.6246125	1624.6125
104	10	2	29	12	4/5	250000	0.804148	804.148

Appendix J: 120 Combinations ToA [ms] Experimental Results 4/4

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	Experimental ToA [s]	Experimental ToA [ms]
105	10	2	29	12	4/5	500000	0.388149	388.149
106	10	2	29	12	4/6	10400	No connection	No connection
107	10	2	29	12	4/6	62500	No connection	No connection
108	10	2	29	12	4/6	125000	1.8506555	1850.6555
109	10	2	29	12	4/6	250000	0.898764	898.764
110	10	2	29	12	4/6	500000	0.422830333	422.8303333
111	10	2	29	12	4/7	10400	No connection	No connection
112	10	2	29	12	4/7	62500	No connection	No connection
113	10	2	29	12	4/7	125000	2.049103	2049.103
114	10	2	29	12	4/7	250000	0.9948655	994.8655
115	10	2	29	12	4/7	500000	0.4992625	499.2625
116	10	2	29	12	4/8	10400	No connection	No connection
117	10	2	29	12	4/8	62500	No connection	No connection
118	10	2	29	12	4/8	125000	2.251086	2251.086
119	10	2	29	12	4/8	250000	1.081637	1081.637
120	10	2	29	12	4/8	500000	0.537838	537.838

Appendix K: 57 Combinations ToA [ms] Experimental Results 1/2

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	Experimental ToA [s]	Experimental ToA [ms]
1	10	2	29	7	4/5	62500	0.178084	178.084
2	10	2	29	7	4/5	125000	0.1090652	109.0652
3	10	2	29	7	4/5	250000	0.0380796	38.0796
4	10	2	29	7	4/5	500000	0.0284202	28.4202
5	10	2	29	7	4/6	62500	0.1965362	196.5362
6	10	2	29	7	4/6	125000	0.1081636	108.1636
7	10	2	29	7	4/6	250000	0.0675732	67.5732
8	10	2	29	7	4/6	500000	0.0309132	30.9132
9	10	2	29	7	4/7	62500	0.2262666	226.2666
10	10	2	29	7	4/7	125000	0.1291258	129.1258
11	10	2	29	7	4/7	250000	0.0568704	56.8704
12	10	2	29	7	4/7	500000	0.0382652	38.2652
13	10	2	29	7	4/8	62500	0.253262	253.262
14	10	2	29	7	4/8	125000	0.1313838	131.3838
15	10	2	29	7	4/8	250000	0.0632582	63.2582
16	10	2	29	7	4/8	500000	0.0540672	54.0672
17	10	2	29	8	4/5	62500	0.300497	300.497
18	10	2	29	8	4/5	125000	0.147669	147.669
19	10	2	29	8	4/5	250000	0.0712464	71.2464
20	10	2	29	8	4/5	500000	0.0424776	42.4776
21	10	2	29	8	4/6	62500	0.3415748	341.5748
22	10	2	29	8	4/6	125000	0.1821744	182.1744
23	10	2	29	8	4/6	250000	0.0786134	78.6134
24	10	2	29	8	4/6	500000	0.0455994	45.5994
25	10	2	29	8	4/7	62500	0.3803134	380.3134
26	10	2	29	8	4/7	125000	0.1890604	189.0604
27	10	2	29	8	4/7	250000	0.115156	115.156
28	10	2	29	8	4/7	500000	0.059169	59.169
29	10	2	29	8	4/8	125000	0.2148256	214.8256
30	10	2	29	8	4/8	250000	0.1062128	106.2128
31	10	2	29	8	4/8	500000	0.0572764	57.2764

Appendix K: 57 Combinations ToA [ms] Experimental Results 2/2

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	Experimental ToA [s]	Experimental ToA [ms]
32	10	2	29	9	4/5	125000	0.278836	278.836
33	10	2	29	9	4/5	250000	0.139119	139.119
34	10	2	29	9	4/5	500000	0.0708678	70.8678
35	10	2	29	9	4/6	125000	0.3083334	308.3334
36	10	2	29	9	4/6	250000	0.150207	150.207
37	10	2	29	9	4/6	500000	0.077996	77.996
38	10	2	29	9	4/7	125000	0.3449912	344.9912
39	10	2	29	9	4/7	250000	0.1772468	177.2468
40	10	2	29	9	4/7	500000	0.0941504	94.1504
41	10	2	29	9	4/8	125000	0.3926112	392.6112
42	10	2	29	9	4/8	250000	0.1866918	186.6918
43	10	2	29	9	4/8	500000	0.0968262	96.8262
44	10	2	29	10	4/5	250000	0.2532028	253.2028
45	10	2	29	10	4/5	500000	0.13781	137.81
46	10	2	29	10	4/6	250000	0.2869412	286.9412
47	10	2	29	10	4/6	500000	0.1442738	144.2738
48	10	2	29	10	4/7	250000	0.3226322	322.6322
49	10	2	29	10	4/7	500000	0.164676	164.676
50	10	2	29	10	4/8	250000	0.3512968	351.2968
51	10	2	29	10	4/8	500000	0.178683	178.683
52	10	2	29	11	4/5	250000	0.22061	220.61
53	10	2	29	11	4/5	500000	0.164983	164.983
54	10	2	29	11	4/6	500000	0.196	196
55	10	2	29	11	4/7	500000	0.243952	243.952
56	10	2	29	11	4/8	500000	0.236316	236.316
57	10	2	29	12	4/5	500000	0.388149	388.149

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 1/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
1	10	4	51	7	4/5	62500	17.17	17.390049	0.220049	220.049	205.31
2	10	4	51	7	4/5	125000	21.998	22.116982	0.118982	118.982	102.66
3	10	4	51	7	4/5	250000	31.792	31.858268	0.066268	66.268	51.33
4	10	4	51	7	4/5	500000	35.452	35.517689	0.065689	65.689	25.66
5	10	4	51	7	4/6	62500	4.911	5.184118	0.273118	273.118	238.08
6	10	4	51	7	4/6	125000	13.462	13.603937	0.141937	141.937	119.04
7	10	4	51	7	4/6	250000	8.824	8.903369	0.079369	79.369	59.52
8	10	4	51	7	4/6	500000	51.542	51.586774	0.044774	44.774	29.76
9	10	4	51	7	4/7	62500	53.393	53.693461	0.300461	300.461	270.85
10	10	4	51	7	4/7	125000	46.151	46.299185	0.148185	148.185	135.42
11	10	4	51	7	4/7	250000	27.066	27.170924	0.104924	104.924	67.71
12	10	4	51	7	4/7	500000	1.984	2.048618	0.064618	64.618	33.86
13	10	4	51	7	4/8	62500	14.305	14.616311	0.311311	311.311	303.62
14	10	4	51	7	4/8	125000	19.424	19.599631	0.175631	175.631	151.81
15	10	4	51	7	4/8	250000	3.827	3.910938	0.083938	83.938	75.9
16	10	4	51	7	4/8	500000	43.795	43.861641	0.066641	66.641	37.95
17	10	4	51	8	4/5	62500	53.376	53.764659	0.388659	388.659	369.66
18	10	4	51	8	4/5	125000	54.773	54.9736	0.2006	200.6	184.83
19	10	4	51	8	4/5	250000	25.262	25.386365	0.124365	124.365	92.42
20	10	4	51	8	4/5	500000	53.314	53.401057	0.087057	87.057	46.21
21	10	4	51	8	4/6	62500	15.901	16.334781	0.433781	433.781	427.01
22	10	4	51	8	4/6	125000	20.001	20.236531	0.235531	235.531	213.5
23	10	4	51	8	4/6	250000	14.691	14.827647	0.136647	136.647	106.75
24	10	4	51	8	4/6	500000	32.658	32.733558	0.075558	75.558	53.38
25	10	4	51	8	4/7	62500	7.601	8.098962	0.497962	497.962	484.35
26	10	4	51	8	4/7	125000	2.927	3.179667	0.252667	252.667	242.18
27	10	4	51	8	4/7	250000	31.491	31.646184	0.155184	155.184	121.09
28	10	4	51	8	4/7	500000	41.098	41.202424	0.104424	104.424	60.54
29	10	4	51	8	4/8	125000	57.843	58.119525	0.276525	276.525	270.85
30	10	4	51	8	4/8	250000	28.104	28.276694	0.172694	172.694	135.42
31	10	4	51	8	4/8	500000	20.747	20.85076	0.10376	103.76	67.71
32	10	4	51	9	4/5	125000	43.678	44.050912	0.372912	372.912	328.7
33	10	4	51	9	4/5	250000	49.57	49.78273	0.21273	212.73	164.35

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 2/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
34	10	4	51	9	4/5	500000	5.643	5.75902	0.11602	116.02	82.18
35	10	4	51	9	4/6	125000	32.816	33.243767	0.427767	427.767	377.86
36	10	4	51	9	4/6	250000	38.895	39.125646	0.230646	230.646	188.93
37	10	4	51	9	4/6	500000	57.078	57.194246	0.116246	116.246	94.46
38	10	4	51	9	4/7	125000	22.711	23.162537	0.451537	451.537	427.01
39	10	4	51	9	4/7	250000	27.661	27.908178	0.247178	247.178	213.5
40	10	4	51	9	4/7	500000	26.388	26.534868	0.146868	146.868	106.75
41	10	4	51	9	4/8	125000	22.033	22.52672	0.49372	493.72	476.16
42	10	4	51	9	4/8	250000	33.221	33.492679	0.271679	271.679	238.08
43	10	4	51	9	4/8	500000	2.235	2.367689	0.132689	132.689	119.04
44	10	4	51	10	4/5	250000	21.743	22.063774	0.320774	320.774	308.22
45	10	4	51	10	4/5	500000	31.353	31.525865	0.172865	172.865	154.11
46	10	4	51	10	4/6	250000	23.932	24.293579	0.361579	361.579	353.28
47	10	4	51	10	4/6	500000	2.453	2.666744	0.213744	213.744	176.64
48	10	4	51	10	4/7	250000	22.838	23.231328	0.393328	393.328	398.34
49	10	4	51	10	4/7	500000	38.491	38.716576	0.225576	225.576	199.17
50	10	4	51	10	4/8	250000	43.927	44.380834	0.453834	453.834	443.39
51	10	4	51	10	4/8	500000	39.244	39.473918	0.229918	229.918	221.7
52	10	4	51	11	4/5	250000	16.432	17.071393	0.639393	639.393	575.49
53	10	4	51	11	4/5	500000	5.119	5.473197	0.354197	354.197	287.74
54	10	4	51	11	4/6	500000	52.559	52.947101	0.388101	388.101	328.7
55	10	4	51	11	4/7	500000	25.142	25.579967	0.437967	437.967	369.66
56	10	4	51	11	4/8	500000	3.73	4.214257	0.484257	484.257	410.62
57	10	4	51	12	4/5	500000	10.806	11.430416	0.624416	624.416	534.53
58	10	5	62	7	4/5	62500	37.145	37.405461	0.260461	260.461	236.03
59	10	5	62	7	4/5	125000	1.854	2.014562	0.160562	160.562	118.02
60	10	5	62	7	4/5	250000	45.279	45.383243	0.104243	104.243	59.01
61	10	5	62	7	4/5	500000	32.011	32.081542	0.070542	70.542	29.5
62	10	5	62	7	4/6	62500	40.035	40.347023	0.312023	312.023	274.94
63	10	5	62	7	4/6	125000	36.327	36.452212	0.125212	125.212	137.47
64	10	5	62	7	4/6	250000	34.257	34.364658	0.107658	107.658	68.74
65	10	5	62	7	4/6	500000	7.795	7.879755	0.084755	84.755	34.37
66	10	5	62	7	4/7	62500	11.423	11.757038	0.334038	334.038	313.86
67	10	5	62	7	4/7	125000	12.602	12.786101	0.184101	184.101	156.93

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 3/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
68	10	5	62	7	4/7	250000	16.708	16.823238	0.115238	115.238	78.46
69	10	5	62	7	4/7	500000	52.143	52.229101	0.086101	86.101	39.23
70	10	5	62	7	4/8	62500	45.884	46.259143	0.375143	375.143	352.77
71	10	5	62	7	4/8	125000	17.804	17.993821	0.189821	189.821	176.38
72	10	5	62	7	4/8	250000	11.406	11.484898	0.078898	78.898	88.19
73	10	5	62	7	4/8	500000	54.788	54.879966	0.091966	91.966	44.1
74	10	5	62	8	4/5	62500	12.508	12.985153	0.477153	477.153	410.62
75	10	5	62	8	4/5	125000	56.948	57.169641	0.221641	221.641	205.31
76	10	5	62	8	4/5	250000	34.603	34.755863	0.152863	152.863	102.66
77	10	5	62	8	4/5	500000	9.771	9.887219	0.116219	116.219	51.33
78	10	5	62	8	4/6	62500	47.691	48.190065	0.499065	499.065	476.16
79	10	5	62	8	4/6	125000	56.132	56.421547	0.289547	289.547	238.08
80	10	5	62	8	4/6	250000	39.049	39.238664	0.189664	189.664	119.04
81	10	5	62	8	4/6	500000	37.354	37.460632	0.106632	106.632	59.52
82	10	5	62	8	4/7	62500	23.399	23.990901	0.591901	591.901	541.7
83	10	5	62	8	4/7	125000	2.575	2.864787	0.289787	289.787	270.85
84	10	5	62	8	4/7	250000	45.606	45.767697	0.161697	161.697	135.42
85	10	5	62	8	4/7	500000	28.261	28.376657	0.115657	115.657	67.71
86	10	5	62	8	4/8	125000	23.939	24.276703	0.337703	337.703	303.62
87	10	5	62	8	4/8	250000	3.302	3.486695	0.184695	184.695	151.81
88	10	5	62	8	4/8	500000	36.499	36.613166	0.114166	114.166	75.9
89	10	5	62	9	4/5	125000	54.569	55.005612	0.436612	436.612	369.66
90	10	5	62	9	4/5	250000	4.227	4.459347	0.232347	232.347	184.83
91	10	5	62	9	4/5	500000	7.807	7.940951	0.133951	133.951	92.42
92	10	5	62	9	4/6	125000	12.047	12.520267	0.473267	473.267	427.01
93	10	5	62	9	4/6	250000	38.383	38.632037	0.249037	249.037	213.5
94	10	5	62	9	4/6	500000	38.645	38.785213	0.140213	140.213	106.75
95	10	5	62	9	4/7	125000	38.268	38.823832	0.555832	555.832	484.35
96	10	5	62	9	4/7	250000	25.785	26.080783	0.295783	295.783	242.18
97	10	5	62	9	4/7	500000	51.032	51.210283	0.178283	178.283	121.09
98	10	5	62	9	4/8	125000	28.762	29.353966	0.591966	591.966	541.7
99	10	5	62	9	4/8	250000	6.883	7.201445	0.318445	318.445	270.85
100	10	5	62	9	4/8	500000	32.88	33.06557	0.18557	185.57	135.42
101	10	5	62	10	4/5	250000	4.673	5.063925	0.390925	390.925	349.18

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 4/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
102	10	5	62	10	4/5	500000	52.361	52.568325	0.207325	207.325	174.59
103	10	5	62	10	4/6	250000	28.286	28.733648	0.447648	447.648	402.43
104	10	5	62	10	4/6	500000	56.434	56.690415	0.256415	256.415	201.22
105	10	5	62	10	4/7	250000	31.288	31.776917	0.488917	488.917	455.68
106	10	5	62	10	4/7	500000	48.595	48.871514	0.276514	276.514	227.84
107	10	5	62	10	4/8	250000	33.533	34.078757	0.545757	545.757	508.93
108	10	5	62	10	4/8	500000	6.234	6.519254	0.285254	285.254	254.46
109	10	5	62	11	4/5	250000	37.492	38.253785	0.761785	761.785	657.41
110	10	5	62	11	4/5	500000	9.034	9.457287	0.423287	423.287	328.7
111	10	5	62	11	4/6	500000	31.398	31.884326	0.486326	486.326	377.86
112	10	5	62	11	4/7	500000	13.94	14.463684	0.523684	523.684	427.01
113	10	5	62	11	4/8	500000	51.064	51.625247	0.561247	561.247	476.16
114	10	5	62	12	4/5	500000	36.922	37.614212	0.692212	692.212	616.45
115	10	7	84	7	4/5	62500	46.874	47.213978	0.339978	339.978	297.47
116	10	7	84	7	4/5	125000	15.516	15.706878	0.190878	190.878	148.74
117	10	7	84	7	4/5	250000	3.279	3.420969	0.141969	141.969	74.37
118	10	7	84	7	4/5	500000	46.846	46.99245	0.14645	146.45	37.18
119	10	7	84	7	4/6	62500	51.591	52.017132	0.426132	426.132	348.67
120	10	7	84	7	4/6	125000	45.575	45.820833	0.245833	245.833	174.34
121	10	7	84	7	4/6	250000	11.216	11.369668	0.153668	153.668	87.17
122	10	7	84	7	4/6	500000	17.395	17.500711	0.105711	105.711	43.58
123	10	7	84	7	4/7	62500	20.296	20.752379	0.456379	456.379	399.87
124	10	7	84	7	4/7	125000	47.578	47.857886	0.279886	279.886	199.94
125	10	7	84	7	4/7	250000	15.935	16.114987	0.179987	179.987	99.97
126	10	7	84	7	4/7	500000	53.52	53.628294	0.108294	108.294	49.98
127	10	7	84	7	4/8	62500	47.714	48.197042	0.483042	483.042	451.07
128	10	7	84	7	4/8	125000	21.289	21.590069	0.301069	301.069	225.54
129	10	7	84	7	4/8	250000	51.048	51.236532	0.188532	188.532	112.77
130	10	7	84	7	4/8	500000	29.458	29.594761	0.136761	136.761	56.38
131	10	7	84	8	4/5	62500	28.762	29.334567	0.572567	572.567	533.5
132	10	7	84	8	4/5	125000	11.421	11.744168	0.323168	323.168	266.75
133	10	7	84	8	4/5	250000	36.483	36.685494	0.202494	202.494	133.38
134	10	7	84	8	4/5	500000	4.165	4.310723	0.145723	145.723	66.69
135	10	7	84	8	4/6	62500	53.455	54.140691	0.685691	685.691	623.62

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 5/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
136	10	7	84	8	4/6	125000	30.572	30.931469	0.359469	359.469	311.81
137	10	7	84	8	4/6	250000	6.833	7.049477	0.216477	216.477	155.9
138	10	7	84	8	4/6	500000	53.554	53.688335	0.134335	134.335	77.95
139	10	7	84	8	4/7	62500	51.637	52.408271	0.771271	771.271	713.73
140	10	7	84	8	4/7	125000	40.415	40.829284	0.414284	414.284	356.86
141	10	7	84	8	4/7	250000	12.866	13.117	0.251	251	178.43
142	10	7	84	8	4/7	500000	33.458	33.625964	0.167964	167.964	89.22
143	10	7	84	8	4/8	125000	12.718	13.1641	0.4461	446.1	401.92
144	10	7	84	8	4/8	250000	3.221	3.459585	0.238585	238.585	200.96
145	10	7	84	8	4/8	500000	28.205	28.350379	0.145379	145.379	100.48
146	10	7	84	9	4/5	125000	46.122	46.663926	0.541926	541.926	472.06
147	10	7	84	9	4/5	250000	30.7	31.007371	0.307371	307.371	236.03
148	10	7	84	9	4/5	500000	1.438	1.626171	0.188171	188.171	118.02
149	10	7	84	9	4/6	125000	12.54	13.14531	0.60531	605.31	549.89
150	10	7	84	9	4/6	250000	43.906	44.24003	0.33403	334.03	274.94
151	10	7	84	9	4/6	500000	7.95	8.146899	0.196899	196.899	137.47
152	10	7	84	9	4/7	125000	59.208	59.887328	0.679328	679.328	627.71
153	10	7	84	9	4/7	250000	34.988	35.371928	0.383928	383.928	313.86
154	10	7	84	9	4/7	500000	11.237	11.438338	0.201338	201.338	156.93
155	10	7	84	9	4/8	125000	54.428	55.186114	0.758114	758.114	705.54
156	10	7	84	9	4/8	250000	29.455	29.852109	0.397109	397.109	352.77
157	10	7	84	9	4/8	500000	0.219	0.480351	0.261351	261.351	176.38
158	10	7	84	10	4/5	250000	57.155	57.660816	0.505816	505.816	431.1
159	10	7	84	10	4/5	500000	27.673	27.931981	0.258981	258.981	215.55
160	10	7	84	10	4/6	250000	55.886	56.439159	0.553159	553.159	500.74
161	10	7	84	10	4/6	500000	35.035	35.358043	0.323043	323.043	250.37
162	10	7	84	10	4/7	250000	7.462	8.092643	0.630643	630.643	570.37
163	10	7	84	10	4/7	500000	41.322	41.669037	0.347037	347.037	285.18
164	10	7	84	10	4/8	250000	38.409	39.121542	0.712542	712.542	640
165	10	7	84	10	4/8	500000	16.707	17.09367	0.38667	386.67	320
166	10	7	84	11	4/5	250000	30.049	31.054738	1.005738	1005.738	821.25
167	10	7	84	11	4/5	500000	33.705	34.259667	0.554667	554.667	410.62
168	10	7	84	11	4/6	500000	10.823	11.444717	0.621717	621.717	476.16
169	10	7	84	11	4/7	500000	44.975	45.646046	0.671046	671.046	541.7

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 6/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
170	10	7	84	11	4/8	500000	26.524	27.287612	0.763612	763.612	607.23
171	10	7	84	12	4/5	500000	19.258	20.222868	0.964868	964.868	739.33
172	10	10	118	7	4/5	62500	12.154	12.633943	0.479943	479.943	399.87
173	10	10	118	7	4/5	125000	40.472	40.778625	0.306625	306.625	199.94
174	10	10	118	7	4/5	250000	21.942	22.167859	0.225859	225.859	99.97
175	10	10	118	7	4/5	500000	54.669	54.818386	0.149386	149.386	49.98
176	10	10	118	7	4/6	62500	47.876	48.429258	0.553258	553.258	471.55
177	10	10	118	7	4/6	125000	47.93	48.295734	0.365734	365.734	235.78
178	10	10	118	7	4/6	250000	37.39	37.615006	0.225006	225.006	117.89
179	10	10	118	7	4/6	500000	28.838	29.022366	0.184366	184.366	58.94
180	10	10	118	7	4/7	62500	21.544	22.176599	0.632599	632.599	543.23
181	10	10	118	7	4/7	125000	46.266	46.641805	0.375805	375.805	271.62
182	10	10	118	7	4/7	250000	22.726	22.951132	0.225132	225.132	135.81
183	10	10	118	7	4/7	500000	54.137	54.32457	0.18757	187.57	67.9
184	10	10	118	7	4/8	62500	14.842	15.551022	0.709022	709.022	614.91
185	10	10	118	7	4/8	125000	38.449	38.864008	0.415008	415.008	307.46
186	10	10	118	7	4/8	250000	57.231	57.500279	0.269279	269.279	153.73
187	10	10	118	7	4/8	500000	22.651	22.838148	0.187148	187.148	76.86
188	10	10	118	8	4/5	62500	25.084	25.913068	0.829068	829.068	697.34
189	10	10	118	8	4/5	125000	0.083	0.560391	0.477391	477.391	348.67
190	10	10	118	8	4/5	250000	35.389	35.676508	0.287508	287.508	174.34
191	10	10	118	8	4/5	500000	1.845	2.052595	0.207595	207.595	87.17
192	10	10	118	8	4/6	62500	45.748	46.680616	0.932616	932.616	820.22
193	10	10	118	8	4/6	125000	1.328	1.861763	0.533763	533.763	410.11
194	10	10	118	8	4/6	250000	20.215	20.56231	0.34731	347.31	205.06
195	10	10	118	8	4/6	500000	5.946	6.197236	0.251236	251.236	102.53
196	10	10	118	8	4/7	62500	13.405	14.464484	1.059484	1059.484	943.1
197	10	10	118	8	4/7	125000	46.218	46.798532	0.580532	580.532	471.55
198	10	10	118	8	4/7	250000	26.722	27.082249	0.360249	360.249	235.78
199	10	10	118	8	4/7	500000	54.801	55.010025	0.209025	209.025	117.89
200	10	10	118	8	4/8	125000	55.697	56.348386	0.651386	651.386	532.99
201	10	10	118	8	4/8	250000	48.834	49.2156	0.3816	381.6	266.5
202	10	10	118	8	4/8	500000	26.246	26.503464	0.257464	257.464	133.25
203	10	10	118	9	4/5	125000	54.237	54.953397	0.716397	716.397	635.9

Appendix L: 57 Combinations ToA [ms] Experimental vs. Theoretical Results 7/7

Test #	Distance [meters]	Sensors	Bytes	SF	CR	BW [Hz]	SEND Time [s]	RECEIVED Time [s]	Experimental ToA [s]	Experimental ToA [ms]	Theoretical ToA [ms]
204	10	10	118	9	4/5	250000	32.283	32.715534	0.432534	432.534	317.95
205	10	10	118	9	4/5	500000	10.62	10.888522	0.268522	268.522	158.98
206	10	10	118	9	4/6	125000	58.812	59.624441	0.812441	812.441	746.5
207	10	10	118	9	4/6	250000	25.225	25.713849	0.488849	488.849	373.25
208	10	10	118	9	4/6	500000	12.472	12.776828	0.304828	304.828	186.62
209	10	10	118	9	4/7	125000	58.92	59.867878	0.947878	947.878	857.09
210	10	10	118	9	4/7	250000	25.661	26.17178	0.51078	510.78	428.54
211	10	10	118	9	4/7	500000	2.103	2.405983	0.302983	302.983	214.27
212	10	10	118	9	4/8	125000	37.484	38.542296	1.058296	1058.296	967.68
213	10	10	118	9	4/8	250000	13.677	14.274651	0.597651	597.651	483.84
214	10	10	118	9	4/8	500000	39.3	39.646925	0.346925	346.925	241.92
215	10	10	118	10	4/5	250000	42.803	43.499577	0.696577	696.577	574.46
216	10	10	118	10	4/5	500000	26.14	26.548998	0.408998	408.998	287.23
217	10	10	118	10	4/6	250000	9.69	10.470074	0.780074	780.074	672.77
218	10	10	118	10	4/6	500000	35.603	36.072651	0.469651	469.651	336.38
219	10	10	118	10	4/7	250000	31.373	32.281904	0.908904	908.904	771.07
220	10	10	118	10	4/7	500000	14.877	15.364075	0.487075	487.075	385.54
221	10	10	118	10	4/8	250000	17.465	18.459805	0.994805	994.805	869.38
222	10	10	118	10	4/8	500000	53.159	53.696447	0.537447	537.447	434.69
223	10	10	118	11	4/5	250000	0.297	1.647711	1.350711	1350.711	1067.01
224	10	10	118	11	4/5	500000	32.174	32.8994	0.7254	725.4	533.5
225	10	10	118	11	4/6	500000	13.39	14.256512	0.866512	866.512	623.62
226	10	10	118	11	4/7	500000	2.777	3.70705	0.93005	930.05	713.73
227	10	10	118	11	4/8	500000	35.249	36.274752	1.025752	1025.752	803.84
228	10	10	118	12	4/5	500000	31.402	32.694542	1.292542	1292.542	985.09