PROTOTYPING AND EVALUATING LORAWAN COMMUNICATION DEVICES

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Advisor Assistant Professor Suppakarn Chansareewittaya, Ph. D.

ABSTRACT

In this research, presents the development and apply a DIY LoRaWAN Gateway operating in the 925MHz frequency band. LoRaWAN technology is renowned for its long-range communication capabilities and low power usage. Currently, it is utilized by only certain groups of users and is not as widespread as Wi-Fi due to the high prices of gateways in the market. Consequently, existing gateways are tailored for devices with reasonable costs. Therefore, we propose designing a cost-effective, moderately sized, customizable, and high-quality gateway that significantly reduces costs.

In this development, utilize Raspberry Pi as the main processing unit and integrate it with LoRaHAT for Pi. We configure the gateway to enable seamless communication between the gateway, EndNode, and NetworkServer, and ensure flexibility in modifying component formats to suit various project requirements.

The goal of this project is to make LoRaWAN technology accessible through efficient, cost-effective solutions that can be self-built and cater to diverse target groups, such as individual users, makers, and smart farm owners. The aim is to facilitate widespread adoption and promote innovation in IoT usage.

Keywords: LoRaWAN, Gateway, Gps Tracker, LoRa

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CHAPTER 1

INTRODUCTION

1.1 Background and Importance of the Research Problem

The first problem of this research is the disappearance of children aged 5-15 years old. Therefore, we developed a tracking device to track children in various situations. For example, when parents take their children to play in a public park, there are many people from children to adults and elderly people. All of them are strangers. Sometimes, criminals or kidnappers may hide in the crowd or when parents are not paying attention to their children. According to the Missing Persons Information Center of the Royal Thai Police, from 2018 to 2023, there were a total of 5,762 missing children aged 5-15 years old. This is a significant number, not including the elderly and young people who are also at risk of being kidnapped or disappearing from home. No one wants this problem or situation to happen. Because sometimes criminals kidnap people for bad purposes and it can be life-threatening. Therefore, we see the importance of this very much.

Years	Number of Missing Children	Male	Female	Age 0 – 5 Y	Age 6 – 10 Y	Age 11 – 15 Y
2561	1445	850	595	287	404	754
2562	1308	774	534	265	382	661
2563	1043	631	412	214	332	497
2564	922	562	360	184	297	441
2565	834	510	324	162	270	402
2566(Jan-Mar)	210	132	78	42	67	101

Figure 1.1 Missing Children 2561-2566

Child disappearance remains a critical issue caused by factors such as crowded environments, brief lapses in supervision, natural curiosity, or abduction. Even a short moment can lead to children becoming separated from their guardians, especially in public places. The chances of safe recovery decrease rapidly over time, particularly within the first few hours. Although solutions such as CCTV and GPS tracking exist, they still have limitations in coverage and energy consumption.

Due to the above problem regarding the incident of missing children from the previous paper study. Therefore, the first version of the tracking device was developed using LoRa data transmission, which is energy efficient and can transmit data over long distances. It was tested using a conventional antenna and could only transmit and receive up to 5 kilometers away. However, the first version of the device is P2P and cannot identify individual devices. It just broadcasts the signal. So, anyone with a receiver can receive the signal without any encryption required. And in transmitting data within a distance of 5 kilometers, there is still signal loss when passing through buildings or obstacles. And the signal range is only -115dBm and the spreading factor cannot be set because it is P2P communication.

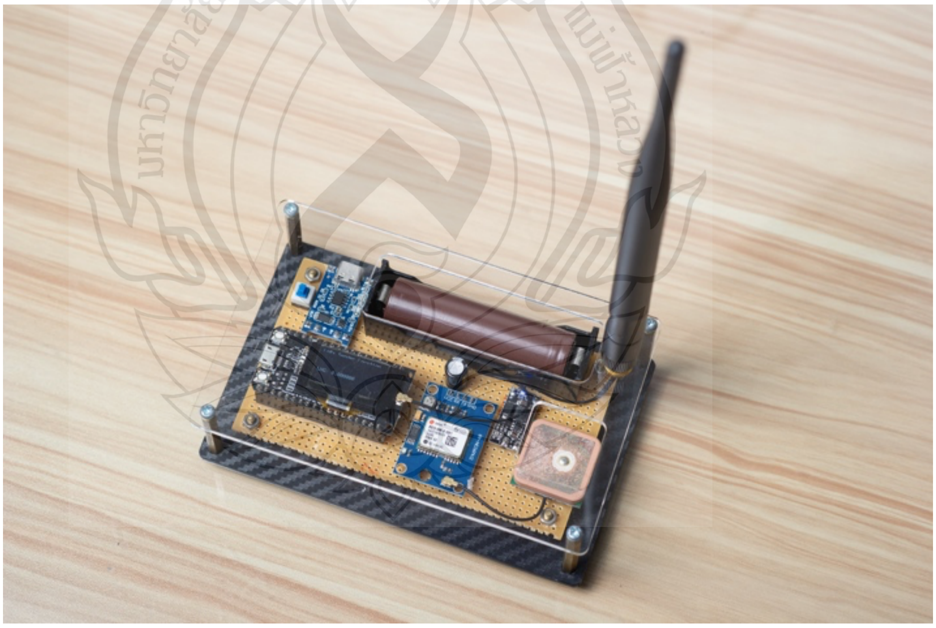


Figure 1.2 First version of the tracking device

After identifying various issues from the experiments show in Figure 1.2, we sought solutions to address and mitigate the encountered limitations. We then turned to using LoRaWAN communication, which is more efficient and secure. LoRaWAN is suitable for IoT applications requiring high security and device encryption during pairing and data transmission. It offers easy network management and supports various customizable configurations.

1.2 Research Objectives

1.2.1 To develop a low-cost and high-quality LoRa gateway for experimentation and application in a variety of real-world scenarios.

1.2.2 Developed and tested a compact tracking device using a LoRa gateway.

1.2.3 Ensure End Nodes can communicate with the Gateway stably and efficiently.

1.3 Scopes of Research

1.3.1 Develop the Gateway to serve as a central communication hub that can be used effectively, utilizing:

1.3.2 Research Gateway data in the market to use as comparative information.

1.4 Expected Result

From some data from this experiment, the Gateway developed has a chance of being partially usable, but there are some difficulties and obstacles in the experiment. Therefore, it is expected that

1.4.1 LoRaWAN Gateway DIY can be done well and completely.

1.4.2 End Nodes used in experiments will be able to communicate with the Gateway well and stably and save energy.

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical Background

2.1.1 GPS & GPS Tracking System

GPS (Global Positioning System) is a system comprised of approximately 24 satellites orbiting the Earth, each at an equal distance from one another. It is this GPS system that enables individuals on the Earth's surface with GPS receivers to determine their own coordinates and location. The accuracy of position determination typically ranges from 10 to 100 meters in most consumer-grade GPS receivers, but specialized military-grade GPS receivers can achieve accuracy up to 1 meter. Initially, GPS receivers were primarily used for scientific purposes. However, due to the decreasing production costs of GPS receivers, they have become accessible to various groups, allowing individuals from all walks of life to acquire and utilize them for personal use(1).

Originally, GPS was developed, created, and held as proprietary by the United States Department of Defense. However, nowadays, it is accessible and usable by all sectors and individuals globally. Here's how GPS works:

2.1.1.1 The primary GPS satellite constellation consists of 21 satellites with an additional three backup satellites. These satellites orbit the Earth at an altitude of 10,600 miles. They are evenly spaced around the globe, and there are four satellites positioned above the horizon at all times.

2.1.1.2 Each satellite comprises a computer system that operates continuously, transmitting radio signals until it expires and decays. All satellites orbit independently, and their onboard clocks are precisely synchronized. However, the position and time information transmitted by each satellite can be continuously adjusted for accuracy. Additionally, each satellite checks the accuracy of its position and time information once per day and can make minor adjustments if needed.

2.1.1.3 Every GPS receiver on the Earth's surface contains a computer system capable of performing 3D triangulation. By receiving signals from at least three of the four satellites, these receivers can determine geographic coordinates, including latitude and longitude.

2.1.1.4 All GPS receivers feature screens capable of displaying maps, overlaying the obtained geographic positions onto the map.

2.1.1.5 Advanced GPS receivers can receive signals from all four satellites, providing additional information about altitude. This information is displayed on the receiver's screen.

2.1.1.6 If in motion, GPS receivers can calculate speed and direction. Moreover, high- end GPS systems can specify destination locations and calculate travel times.

A GPS tracking system is a method of determining the location of an object through the Global Positioning System (GPS), used to track and pinpoint the position of that object from a distance. This GPS tracking technology can accurately identify geographic coordinates, latitude, longitude, ground speed, direction, and movement trajectory of the tracked object. In modern times, communication can occur through various methods, such as transmitting data via GSM, Bluetooth, or WiFi, or through low-frequency radio protocols like LoRaWAN, which enable long-range communication. Besides using GPS alone, tracking can also be achieved through RFID systems, though this type of tracking is more akin to checkpoint-based tracking.

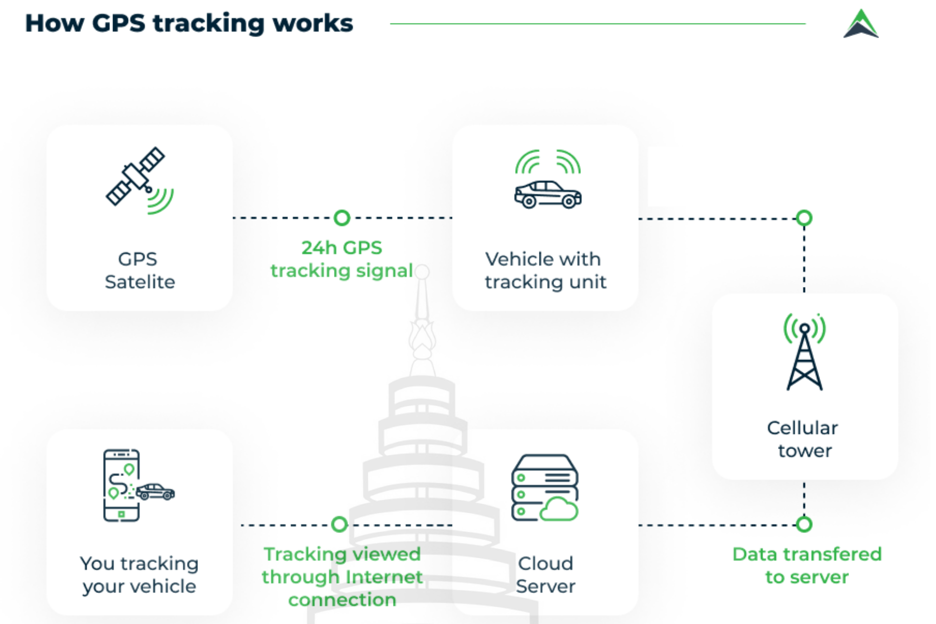


Figure 2.1 How GPS Tracking works

Figure 2.1, Shows the operation of GPS tracking. When GPS tracking is activated, the module connects to satellites in space and sends location coordinates to the module for ground reception to detect the Lat, Lng positions, and speed at that moment. There will be a processor, and communication means such as 4G (GSM) or other communication methods. Communication is transmitted via the internet (4G) to the cloud to store data and display real-time data on our mobile screen.

2.1.2 LoRa & LoRaWAN

LoRa stands for Long Range Radio, a new wireless protocol designed precisely for long-distance connectivity and low-power communication. It utilizes sensors and actuators for Machine-to-Machine (M2M) and Internet of Things (IoT) applications. The system operates using radio spectrum in unlicensed industrial, scientific, and medical bands to facilitate communication over wide areas between long-range sensors and gateways connected to the network. By employing a wider spectrum spread, LoRa technology uses modulation techniques to enhance receiver sensitivity, making it ideal for IoT applications where data mainly originates from various sensors. It’s widely adopted by leading microcontroller developers who design devices to support LoRa connectivity. The technology excels in communication range, capable of transmitting data over distances of 15-20 kilometers, connecting to millions of nodes, boasting long battery life, and conserving energy by utilizing low-power consumption during data transmission. Additionally, devices can be set to energy-saving modes when not transmitting data, reducing costs. This technology enables multiple tenants or public network providers to connect numerous applications on the same network. Moreover, LoRa networks can coexist with cellular networks, with LoRa service providers often being mobile network operators utilizing existing signal towers to install LoRa antennas. Sometimes, LoRa antennas can be integrated with cellular network antennas due to their close frequencies, resulting in significant cost savings.

LPWAN stands for “Low-Power Wide-Area Network”. It is a wireless technology that uses low power to transmit data over long distances. LPWAN is designed to connect low-bandwidth IoT (Internet of Things) devices, with a focus on energy efficiency.

LoRaWAN stands for “Long Range Wide Area Network”. It is a communication protocol for wireless networks used for data communication in IoT devices. It is an open-source LPWAN networking protocol that uses LoRa technology, developed by the LoRa Alliance, which allows other companies to build their own IoT networks using the specifications of this technology. The standardized approach to building LPWAN enables rapid deployment of both private and public IoT networks anywhere using secure, interoperable, and flexible hardware and software. This allows them to meet end-user requirements and operate as desired.

LoRaWAN, data transmitted between devices is packed into small-sized data called payload and sent through communication channels within the LoRaWAN system. Generally, the payload consists of encoded data and formatted appropriately for transmission over radio waves channels. For example, converting text into binary format or other numerical bases. When the data is sent to the LoRaWAN server, what will be received back is a confirmation that the data has been sent or not.

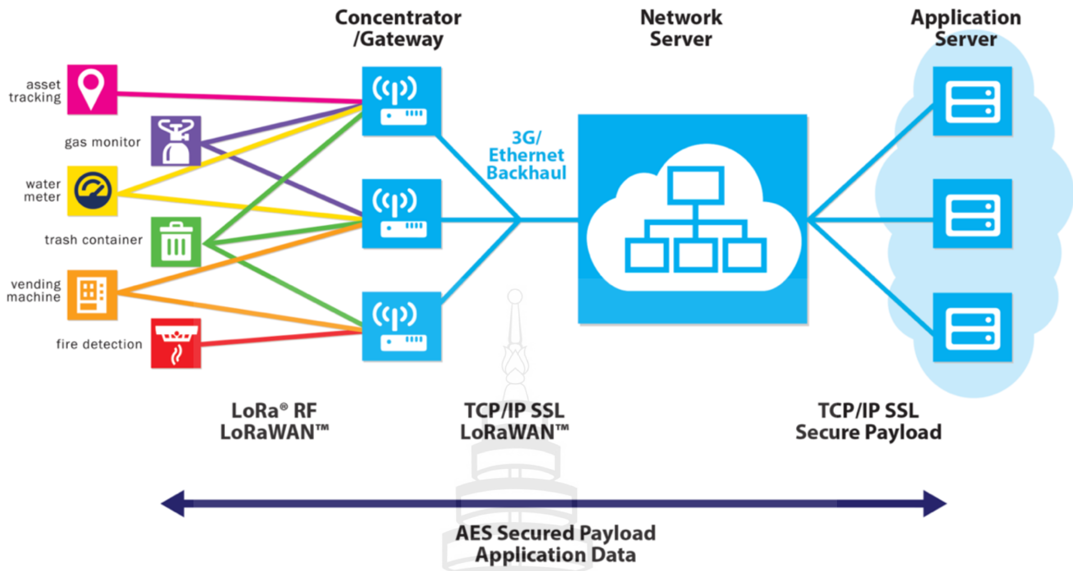


Figure 2.2 LoRaWAN Structure

2.1.3 LoRaWAN comprises three main components

1. End Devices in the LoRaWAN system are devices that communicate with gateways to send data to the network server and receive data back from the server. These devices can be sensors, communication modules, or other devices that need to operate within the LoRaWAN system according to their specific applications. In the LoRaWAN structure show in Figure 2.2, end devices can transmit data over long distances without requiring much power and can operate for extended periods using long-lasting batteries(2).

2. Gateway is a network device for LoRa and LoRaWAN communication that can receive signals sent from end-node devices. It acts as a bridge between network nodes, processing signals and routing them to the appropriate LoRa application. Typically, a LoRa network will have multiple gateways. Additionally, LoRa gateways are designed to listen to multiple radio frequencies simultaneously.(3)(4).

3. Network Server is responsible for overseeing and managing all communication processes. Typically, it operates as a cloud platform within the LoRaWAN network and operates through software applications installed on the cloud system. Its main responsibilities include ensuring the security of LoRaWAN connections, verifying the accuracy of user device credentials before sending them to

the server, preventing external interference, overseeing and creating confidence in establishing appropriate two-way data paths from End nodes to the LoRa application, especially UPLINK, or communication from the LoRa application to the end node. It enhances the battery life efficiency of LoRa-based end devices to maintain battery life and integrity, as well as the overall performance of the LoRa and LoRaWAN communication network.

2.1.4 LoRaWAN utilizes two-layer technologies as follows

1. LoRa serves as the Physical Layer for transmitting LoRa radio signals. LoRa employs Chirp Spread Spectrum (CSS) modulation techniques, enabling long-range transmission and resilience against interference.

2. LoRaWAN operates as the MAC (Media Access Control) layer, responsible for managing medium access and security. LoRaWAN defines methods for establishing connections between end-devices, gateways, and network servers. It specifies data transmission formats, security mechanisms, and device management protocols.

2.1.5 LoRaWAN Device Class

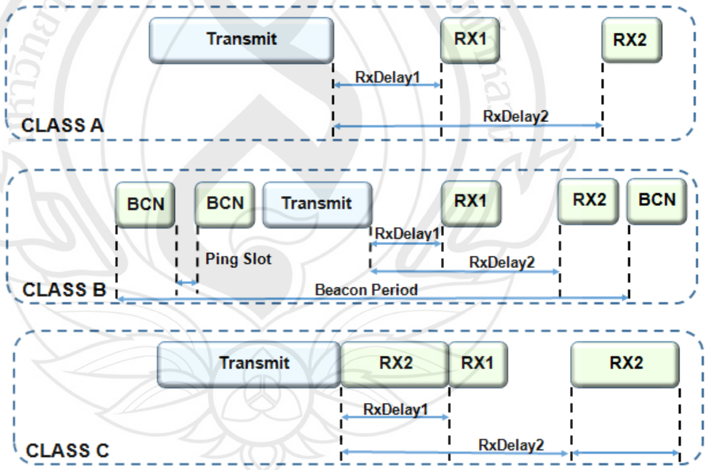


Figure 2.3 LoRa Class A-C

According to LoRaWAN specifications, devices are categorized into three types as shown in the Figure 2.3, All devices must operate under Class A as a basic requirement, while Class B and Class C serve as extensions to the Class A device specifications (5)

1. Class A: Devices of Class A support bidirectional communication between the device and the Gateway. Sending messages from the Device to the Server can occur at any time, with the Device opening two receive windows at predetermined times (1 second and 2 seconds) after transmitting a message.

2. Class B: Devices in Class B extend capabilities from Class A by adding additional receive windows to receive messages from the Server in beacon formats, synchronizing timing for communication between the Gateway and the Device. The Device periodically opens receive windows.

3. Class C: In addition to the Class A structure of uplink followed by two downlink windows, Class C also helps reduce downlink latency by keeping the receiver's signal open all the time when the device is not transmitting (half duplex). Consequently, the network server can initiate downlink data transmission at any time assuming that the end device receiver is open, thus eliminating latency. The compromise is the energy drain of the receiver (up to ~ 50mW), making Class C suitable for continuous energy usage scenarios. For battery-powered devices, they can switch temporarily between Class A and C modes, beneficial for non-continuous tasks such as over-the-air firmware updates.

Table 2.1 Comparing the usage of Class A to Class C

Feature	Class A	Class B	Class C
Data transmission	Uplink-only	Uplink/Downlink	Uplink/Downlink
Energy saving	High	Median	Low
Flexibility	Low	Median	High
Usage	Equipment that needs to save energy	Devices that require two-way communication	Devices that require low-latency, two-way communication

The Comparing the usage of Class A to Class C is shown in Table 2.1 The choice of class depends on the requirements of each application and the importance of energy saving and response time of the communication system in each case, particularly.

The NBTC permits the use of LoRaWAN in the frequency band of 920-925 MHz with a maximum transmission power of not more than 4 watts. LoRaWAN devices used in Thailand must comply with the AS923 standard that show in Table 2.2, and other LoRa frequency bands are as follows

Table 2.2 The frequency bands used by each country

Region	Frequency
Europe, Russia, India	863-870 MHz
North America	915 MHz
Asia	433,920-925 MHz
Australia	915-928 MHz
Canada	779-787 MHz
China	779-787,470-510 MHz

2.1.6 The Spreading Factor

The Spreading Factor (SF) of LoRaWAN is a parameter used to determine the spreading technique of LoRaWAN signals across frequency channels. SF affects both communication range and can be configured from SF7 to SF12. If we aim to operate with a higher bandwidth, we should set the SF to SF7, which results in shorter transmission distances but higher data rates (bit rate). Conversely, if we require longer transmission ranges, we should set the SF to SF12, which minimizes data transmission rates but maximizes communication distances. The parameter settings depend on the system designer's requirements. The data rate of LoRaWAN ranges from SF7 to SF12 and has the following relationship with communication

1. A higher Spreading Factor (SF12) enables signals to be transmitted over a greater distance compared to a lower Spreading Factor (SF7).

2. A higher Spreading Factor (SF12) results in a lower data rate compared to a lower Spreading Factor (SF7).

3. Higher Spreading Factors consume more energy than lower Spreading Factors.

An example of the relationship with communication is as follows

4. SF7: Communication range of 5 kilometers, data rate of 5 kbps.

5. SF12: Communication range of 15 kilometers, data rate of 0.25 kbps.

The Spreading Factor is a crucial parameter in determining the operation of LoRaWAN. Users must select an appropriate SF value based on their usage requirements.

2.1.7 Bandwidth

In LoRaWAN, bandwidth refers to the range of frequencies available for transmitting data within the LoRa physical layer. It represents the amount of data that can be transmitted over a given period of time. LoRaWAN operates in different frequency bands, typically in the sub-GHz range (e.g., 868 MHz in Europe, 915 MHz in North America), and the bandwidth can vary depending on the specific regulations and frequency allocations in each region.

The bandwidth in LoRaWAN determines the rate at which data can be transmitted and the capacity of the network to handle multiple devices simultaneously. It is often categorized into different configurations, such as 125 kHz, 250 kHz, or 500 kHz. A wider bandwidth allows for higher data rates but may result in shorter range and increased power consumption. Conversely, a narrower bandwidth provides longer range and better penetration through obstacles but at the cost of lower data rates.

2.1.8 Security in LoRaWAN

Security should be a primary concern in any IoT application. Maintaining confidentiality, integrity, and availability in multiple aspects is essential. LoRaWAN leverages AES encryption algorithms and 128-bit keys for end device security (identified by a unique name, IEEE EUI64 address, DevEUI). It can utilize two distinct processes for key exchange and distribution for LoRaWAN joining: Over-the-Air Activation (OTAA) and Activation by Personalization (ABP). In OTAA, the two root keys are transmitted over the air, which is then used in conjunction with the received data during the actual key session establishment process. Conversely, in ABP mode, all relevant data is stored within the node, eliminating the need for joining procedures.

Maintaining the confidentiality and integrity of MAC commands can be achieved at the network level, while user data confidentiality is implemented at the application level. Since the latest specifications, additional join and network session keys have been defined to enhance security and flexibility.

2.1.9 OTAA and ABP (End Nodes Join Request)

Before a LoRa-Node can communicate with the Network Server, it is necessary to authenticate and verify the connection rights to the LoRaWAN network. Only then can data transmission occur. This process must be performed each time the device is powered up. There are two available options: the first is OTAA (Over-The-Air Activation), and the second is ABP (Activation-By-Personalisation).

1. OTAA (Over-the-Air Activation): This method allows end devices to join the network by sending key session setup messages over the air during wireless communication to the gateways and LoRaWAN network. It has the advantage of following appropriate security protocols and is suitable for devices that may be mobile or changing positions.

2. ABP (Activation by Personalization): In this method, encryption data and session keys are pre-configured and written directly into the end devices. The devices can then start communicating with gateways and the network directly without needing to go through the network joining process each time they are powered up

2.2 Related Works

In this section, we will discuss the work related to the first paper on LoRa GPS Tracker. In this part of the project, the task involves creating a tracking device using ESP32 and M2M or P2P communication, which is communication between devices. The primary issue of this initial research is missing children, with the objective being to track children or vehicles. Through experimentation in the initial research, various problems were identified sequentially. Firstly, the device is too large and not easily portable, and its Point-to-Point communication capability makes it incompatible with multiple devices. Additionally, there is currently no security or encryption.

Furthermore, the maximum communication range tested is only 5 kilometers. Beyond this distance, communication becomes unreliable or completely lost (6)(7).

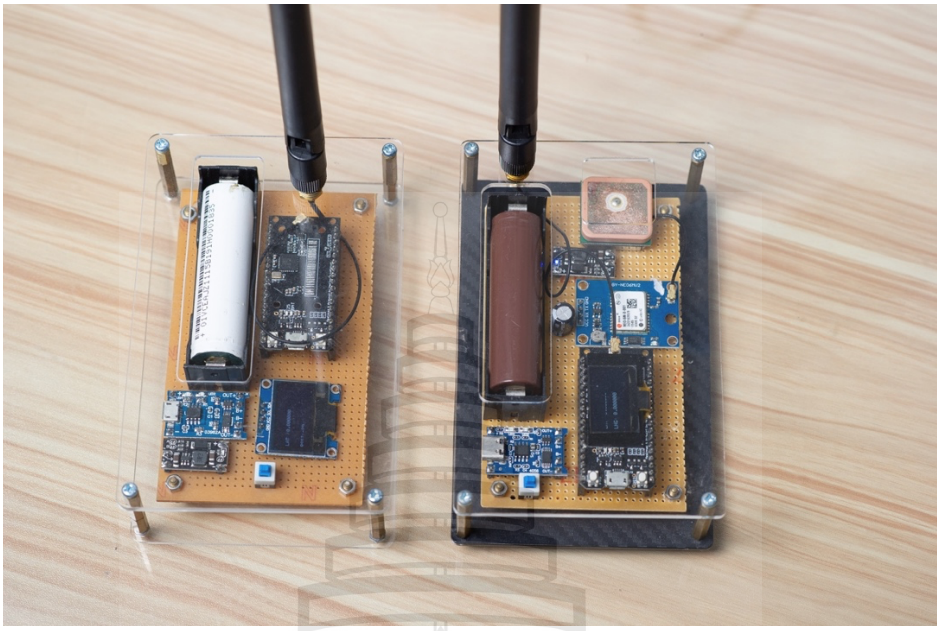


Figure 2.4 First version of GPS Tracker

The first version of the tracker device is shown in Figure 2.4 utilizes P2P communication using LoRa protocol, employing the sx1276 chip at 915MHz frequency for data transmission. The left side functions as the receiver, displaying received LAT, LNG coordinates and forwarding them to a Cloud Application. On the right side is the transmitter or End Node, which receives LAT, LNG data from GPS and broadcasts it outwards for reception without any encryption (1). In this research, LoRaWAN connectivity is employed, ensuring secure encryption and clear separation of DeviceEUI.

When comparing data between LoRa M2M and LoRaWAN, the following differences can be observed:

Table 2.3 Comparing LoRa M2M protocol and LoRaWAN

Feature	LoRa M2M	LoRaWAN
Protocol	LoRa	LoRa
Network structure	Point-to-Point	Star
Security measures	Minimum	High
Device management	Hard	Easy
Device compatibility	Limit	various
Communication range	2-5 Km	5-10 Km
Energy consumption	Low	Low
Cost	Low	High

From the overall comparison and experimental data show in the Table2.3, it is evident that there are clear differences in both increased range and device management. When dealing with a larger number of devices, utilizing LoRaWAN would simplify management due to its more systematic approach. This will be demonstrated with methods and data in subsequent sections. Additionally, the cost of LoRaWAN increases because additional gateways are required to act as intermediaries for communication and management of these devices.

Real-world use cases of LoRaWAN

1. Smart Agriculture: Monitoring soil moisture, temperature, humidity, and crop health remotely to optimize irrigation and crop yields (8).

2. Smart Parking: Providing real-time information about available parking spaces to reduce traffic congestion and help drivers find parking spots more efficiently (9).

3. Traffic Management: Monitoring traffic flow, detecting accidents, and optimizing traffic signal timings to improve road safety and reduce congestion (10).

4. Healthcare: Remote monitoring of patients' vital signs, medication adherence, and medical equipment to improve patient care and reduce hospital readmissions (11).

CHAPTER 3

METHODOLOGY

3.1 Research Overview

This study is qualitative research aimed at creating Low Cost LoRaWAN gateways and designing them to meet the needs of all target groups. This is achieved by selecting readily available and widely marketable components at affordable prices and high quality. These gateways should be adaptable to a variety of devices and situations. In this research, GPS nodes are used, with development up to version 2, which will be tested for transmission range and communication with the gateway to determine the performance of the custom-configured gateway. With these various settings, the gateway itself can operate efficiently and flexibly depending on user preferences. Once the gateway is successful, it can monitor various values from end nodes, displaying them on an open-source dashboard, including gateway statuses.

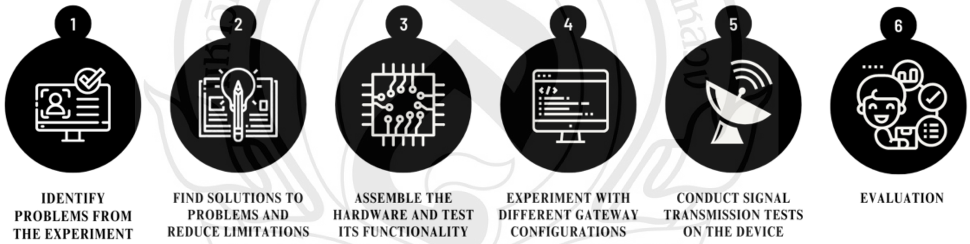


Figure 3.1 Process of Methodology

Figure3.1, Show the research process consists of 6 main steps. It begins with identifying problems from preliminary experiments and exploring possible solutions to address these issues and reduce existing limitations. In this study, the main problem is related to missing persons, which led to the development of a tracking device. However, the first version of the device had several limitations. After identifying the problems and determining appropriate solutions, the next step is hardware assembly and functional testing. Subsequently, the gateway is configured in various setups to determine which parameters provide the most effective and standard-compliant performance. This is followed by testing signal transmission between the gateway and the end device to evaluate communication efficiency. Finally, the experimental results are assessed to determine the overall performance of the developed device and its feasibility for real-world applications.

In Figure 2.4, First Prototype P2P Tracker was developed using a TTGO ESP32 board, an SX1276 chip for LoRa communication, and a NEO-6M GPS module for location tracking. This device operates using LoRa machine-to-machine (M2M) or peer-to-peer (P2P) communication, meaning that data is transmitted directly from one device to another. After development and testing, the device was able to communicate over a distance of up to 5 km under line-of-sight conditions without obstacles. The received signal strength indicator (RSSI) was measured at -115 dBm, which represents the maximum effective range of this prototype.

However, several limitations were identified. The system is not suitable for supporting multiple end devices, as the P2P communication model follows a star-like topology with a limited coverage area. In addition, the payload is not encrypted, which may lead to security issues in future applications. The system also lacks the ability to uniquely identify each device, making it difficult to distinguish between multiple nodes.

Due to these limitations, the system was redesigned to use LoRaWAN, where a gateway acts as an intermediary for communication. This approach enables better data management, improved security, and greater communication range, making it more suitable for scalable and real-world applications.

3.1.1 Details/specifications of your targeted group of participants

The gateway itself can be applied to various purposes such as tracking devices, air quality monitoring, rainfall measurement, energy consumption monitoring, irrigation control for farmers, or vehicle tracking, among others. Due to its relatively small size, the gateway can be portable in some situations and adaptable to many scenarios and purposes. Therefore, the main target groups include

1. IoT Developer
2. Person who wants to monitor their belongings for security purposes
3. National Park
4. Farmer who wants to implement IoT in their farming operations
5. Trail running organizer

3.1.2 Data Collection Method

This research is an experiment on data transmission using the LoRaWAN protocol between Gateways and End nodes. The experiment will involve specific data collection requirements, which are designed as follows:

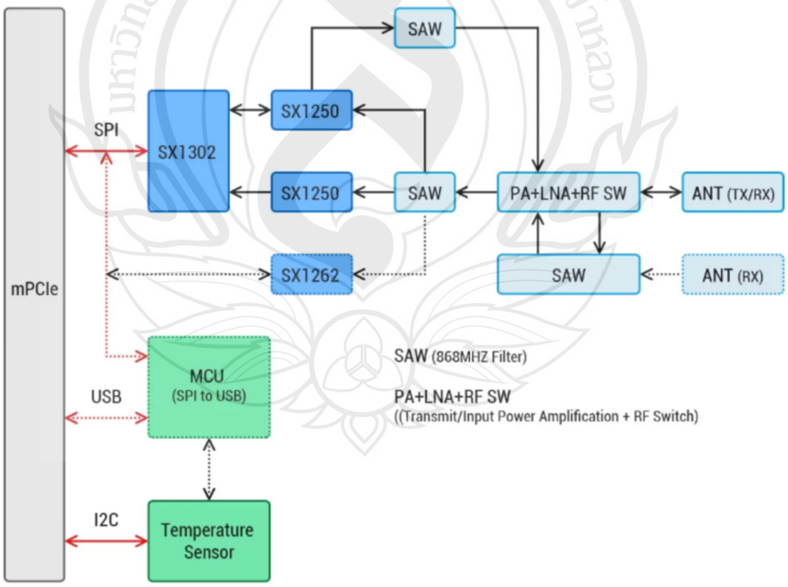
1. Date & Times
2. The payload communicates between end nodes and gateways.
3. Device information ex. antenna model, and gateway ID.
4. Gateway Config ex. SF, Data Rate, Transmit Power.
5. Receive and transmit data ex. RSSI, SNR, Payload Size.

3.2 Method Overviews

In this research, a low-cost LoRaWAN gateway is developed by assembling readily available hardware components from the market at an affordable price. The gateway functions as a central signal distribution point. The development concept utilizes the Raspberry Pi 4 as the primary processing unit for all tasks, coupled with the LoRa HAT sx1302 module for LoRaWAN network management, including both uplink and downlink communications. The research operates at a frequency of 923MHz, with a data transmission rate set to SF12. This choice is made because data encoded in base64, such as latitude and longitude, requires consideration of various data rate limitations. The initial configuration experiments utilize SF12 to determine the optimal settings for future operations (12)(13).

Figure 3.2 LoRaWAN Gateway low cost

The LoRa HAT used for experimentation employs the LoRa SX1302 chip for LoRa communication via SPI, along with other components interfaced through I2C, as shown in Figure 3.2



Source (12-13)

Figure 3.3 SX1302 Architecture

Figure 3.3, shows The LR1302 module is a LoRaWAN module designed in mini-PCIe form factor, utilizing low power and high efficiency. The LR1302 module uses Semtech Network's SX1302 LoRaWAN baseband chip, which offers long-range wireless signal transmission capabilities. When compared to previous LoRa chips like the SX1301 and SX1308, the SX1302 chip has higher speed, lower power consumption, and operates at lower temperatures. It supports 8 channels for data transmission, improving communication efficiency and capacity. Additionally, it supports connection and data transmission for various devices. While there are many LoRa chips available in the market, we chose the SX1302 model because it is convenient to use, robust, and importantly, it has a standby current consumption of only 7.5mA and a wide communication range of up to -139dBm (when using SF12), making it suitable for many applications.

3.2.1 Gateway

```
"gateway_conf": {
    "gateway_ID": "BB555A0000000002",
    "server_address": "au1.cloud.thethings.network",
    "serv_port_up": 1700,
    "serv_port_down": 1700,
    "keepalive_interval": 5,
    "stat_interval": 10,
    "push_timeout_ms": 100,
    "forward_crc_valid": true,
    "forward_crc_error": false,
    "forward_crc_disabled": false,
    /* GPS configuration */
    "gps_tty_path": "/dev/ttyS0",
    "gps_enabled": false,
    /* GPS ref coordinates */
    "ref_latitude": 0.0,
    "ref_longitude": 0.0,
    "ref_altitude": 0,
    "beacon_period": 0,     /* 0=disable class B beacon, 128=enable beacon */
    "beacon_freq_hz": 923400000,
    "beacon_freq_nb": 1,
    "beacon_freq_step": 0,
    "beacon_datarate": 9,
    "beacon_bw_hz": 125000,
    "beacon_power": 26
},
```

Source (14)

Figure 3.4 Main Part of Gateway Config

In Figure 3.4, Gateway configuration section, in the form, it will be the main configuration part. There are several important parameters, starting with the gateway

ID, which is the ID number of the LoRa chip we are using. The ID will be unique and assigned to each individual gateway. Next is the server address, where we can choose to use any network server, whether it's a ready-made one online or a locally hosted one. Following that are the up/down ports, which depend on the chosen network server. For this experiment, the datasheet specifies port 1700 for both up and down. Then there's the CRC check part (Cyclic Redundancy Check), which verifies the correctness of the data sent through the signal channel by checking the bit sequence. Subsequent parameters include values such as keepalive, push timeout, and others. Next is the GPS that is attached to the gateway to determine its position and reference time in case there is no internet connection. In the configuration image, it shows selecting the port for connecting the GPS hardware, and then there's the beacon, which is the transmission of Class B data for LoRa. This configuration option is disabled because this experiment uses Class C and Class A for testing.

Figure 3.5 Gateway receive packet from End Node

In Figure 3.5, it shows the section for receiving packets from the end node. The incoming data will provide various details such as payload size, RSSI, timestamp, the frequency that was sent, and the duration of receiving. There will be timestamps for all of these. The data at the top will be information from the gateway itself and which signal channel the data is being sent from.

3.2.2 Network Server

The Network Server is a part of the LoRaWAN network, which typically serves as the backbone of the LoRaWAN infrastructure. Its main function is to receive data from various devices connected to the LoRaWAN network and then forward this data to applications or services as specified by the user. Additionally, it handles data encryption and manages device connectivity within the network. Having an efficient and reliable LoRaWAN Network Server is crucial in building an effective LoRaWAN infrastructure. In this development, we have opted for SaaS (Software as a Service) because it offers an open and cost-free network participation, allowing easy access and usage with freedom for software development and customization. Moreover, it ensures high-performance systems for support and maintenance, ensuring a stable network capable of providing satisfactory service.

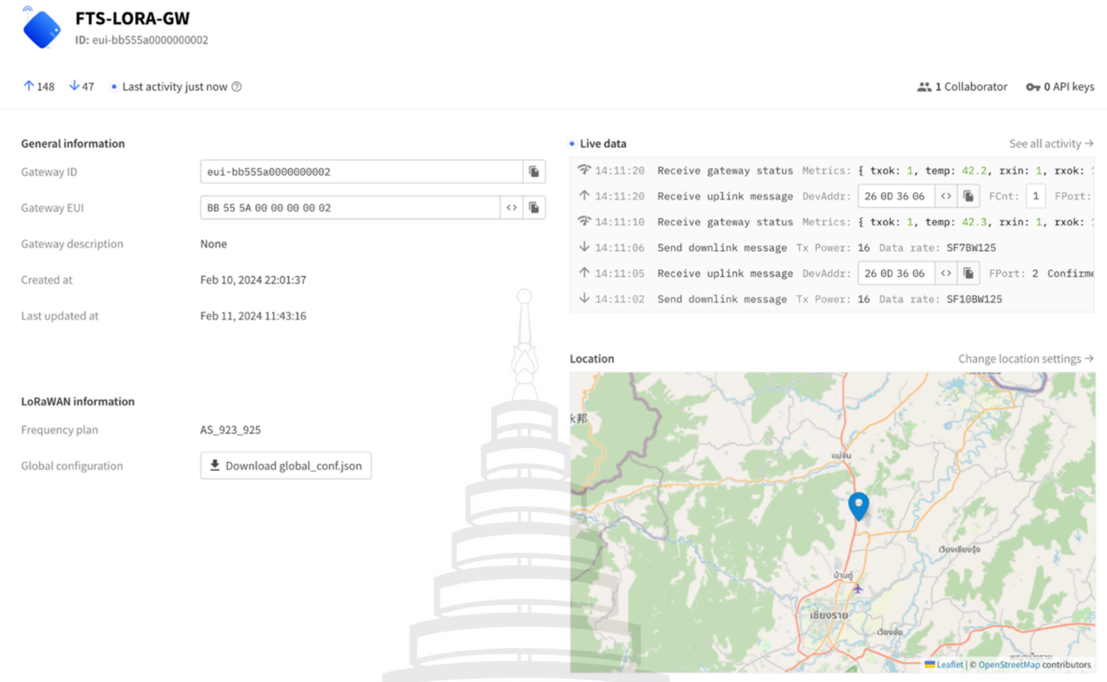


Figure 3.6 Network Server Dashboard

Figure 3.6 shows the status of an online gateway, which includes the gateway's name and its ID. The "Live data" section represents packets coming from the end nodes, also known as uplink. The "downlink" refers to communication from the Network Server to the End Device being tested, which is not yet complete, experiencing payload sending issues to the gateway. The Location section indicates that the gateway has a GPS module attached to determine its position, displayed on the website to show the locations of the gateways. This information can be used to calculate signal propagation distance and synchronize time.

3.2.3 End Nodes

End nodes in the LoRaWAN system are devices that serve as the endpoints of the network. These devices can be various types of equipment connected to the LoRaWAN network to wirelessly transmit data to gateways, which are then forwarded to the Network Server for further processing. These devices are often sensors or detectors that transmit data related to environmental conditions or other tracked data, such as temperature sensors, humidity sensors, smoke detectors, motion detectors, or even tools for measuring various parameters in agriculture or environmental monitoring.

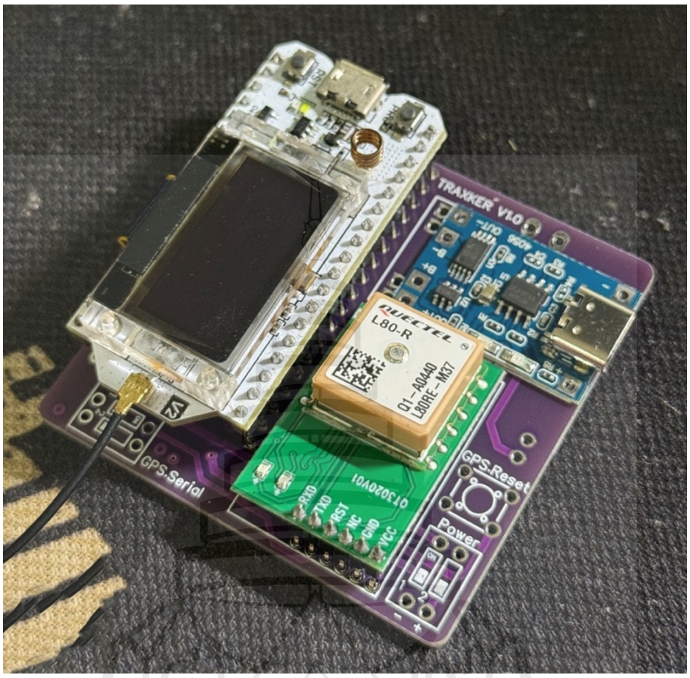


Figure 3.7 End nodes (GPS trackers)

Figure 3.7, Shows a GPS module, also known as a GPS Tracker, as an example of communication with a gateway. The end nodes consist of an ESP32 as the main processor and utilize the SX1276 LoRa chip. They are equipped with the GPS Sensor L80R and a lithium-ion battery module. Therefore, this board utilizes a slim lithium-ion battery, making it compact and portable, suitable for carrying in a backpack or mounting on a vehicle.

3.2.4 Comparing with commercially available gateways

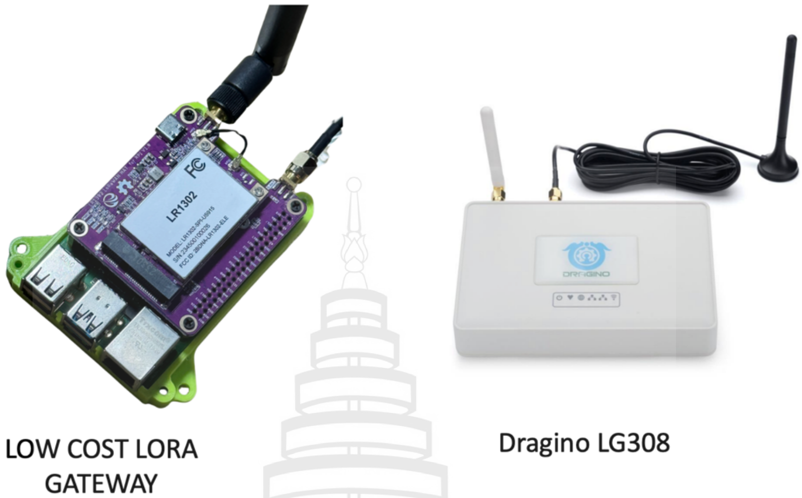


Figure 3.8 Comparing LOW-Cost Gateway and Dragino LG308

Figure 3.8, In the market, there are only a few brands of Gateways available because LoRaWAN has a niche group of interested individuals, which results in higher prices. The gateway being compared will be the Dragino brand, with Multichannel.

Table 3.1 Comparing LOW-Cost Gateway and Dragino LG308

Feature	LOW-COST LORA GATEWAY	DRAGINO LG308
LoRa Chipset	SX1302 + 2x SX1250	SX1302 + 2x SX1257
Max Output Power	25dBm	27dBm
Power Consumtion	5V 2A	12V 1A
TX sensitivity	-139dBm	-142.5dBm
Price	100 USD	350 USD

Table 3.1, From the table, it's evident that the market-available unit prices are significantly higher than our gateway by up to 3.5 times. Moving on to the TX sensitivity, the market-available units have a width of up to 142.5 dBm, while our developed unit has a width of 139 dBm, which is less by only 2.52%. Given the significant price difference, this is acceptable. Another key point is the Max Power Output, where the market-available units exceed by 2 dBm. However, considering the price comparison, it remains acceptable because this specification at this price point is worthwhile and usable in practical applications.

The LG308 is a compact gateway with certain performance limitations due to its use of an older chipset. Its stability is relatively moderate, particularly when operating over a 4G network. In addition, its signal performance is at a moderate level and requires further tuning to achieve optimal results. The device also requires considerable configuration and is primarily designed for indoor use, resulting in limited coverage range.

In comparison, a DIY gateway offers greater flexibility and advantages. It allows full customization based on specific requirements, without firmware restrictions. Users can freely select and configure hardware components according to their needs, enabling complete system customization.

3.3 Research Plan

Table 3.2 Research Planning

Task	2022		2023										2024											
	Nov	Dec	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
P2P End Nodes Signal Range TEST																								
1st publication																								
Design New circuit for End Nodes to small																								
Find solutions to problems and reduce device limitations																								
Assembly hardware for gateway																								
Write a Proposal																								
Proposal Examination																								

Table 3.2 (continued)

Task		2022				2023										2024			
	Nov	Dec	Mar	Nov	Dec	Mar	Nov	Dec	Mar	Nov	Dec	Mar	Nov	Dec	Mar	Nov	Dec	Mar	Nov
Troubleshoot device communication problems																			
Collect the results of the signal transmission experiment																			
Evaluate and summarize the experimental results																			
Write a 2nd Conference																			
2nd publication (ICSEC 2024)																			
Write Thesis report																			
Defense Examination																			

3.4 Evaluation Methods

The evaluation of the experiment in this paper will be divided into various parameters for comparison with previous experiments, assessing signal quality and performance. The parameters include:

1. RSSI
2. Spreading Factors
3. Distance for communication
4. Payload size

3.5 Expected Research Outcome

The expectation for this development is that the DIY LoRaWAN Gateway will be fully functional and efficient, capable of serving as a reliable intermediary for transmitting signals effectively. It is hoped that it will be widely adopted by the target audience and meet their specific usage needs. Additionally, it is hoped that it will be further developed to maximize its benefits

CHAPTER 4

RESULTS

In this experiment, we developed a LoRa gateway as an intermediary for communication between the network server and end nodes to extend the signal coverage of tracking devices from the end nodes. Additionally, we displayed the tracking device status on the dashboard and decoded the payload received from the end nodes.

4.1 Experimental Result on Connectivity, Display and Payload Decoding

The image shows that the End Node device has successfully transmitted data through the Gateway to The Things Stack, without any packet loss. The main data type is 'Receive uplink message,' which is the message sent by the End Node device to the Gateway. Additionally, the transmitted data shows a continuous increase in the Frame Counter, indicating that the device is operating and transmitting data normally. The Data Rate used is SF7BW125 and SF10BW125 (Spreading Factor 10 and Bandwidth 125 kHz), which demonstrates the configuration of data transmission based on distance and connection conditions. Furthermore, the Gateway periodically sends operational status, indicating that the system is functioning well with no issues in the connection between the End Node, Gateway, and The Things Stack. This ensures that the transmitted data can be used correctly and reliably."

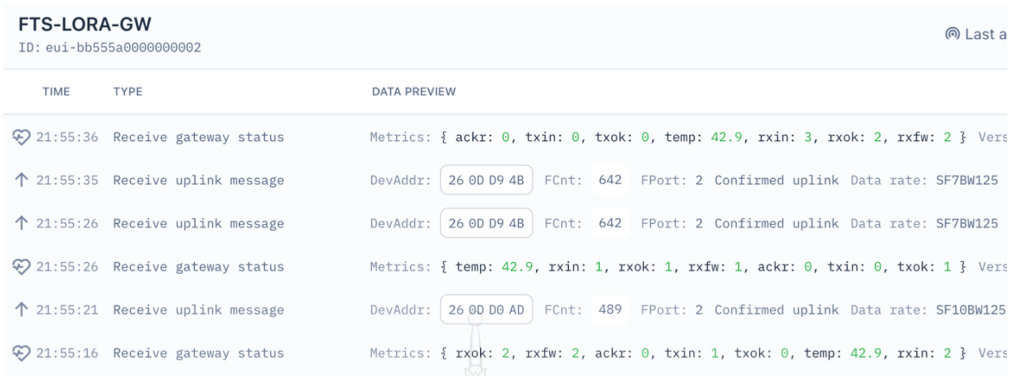


Figure 4.1 Gateway Receive data log

The application's dashboard displays information that show on Figure 4.1 about the connected End Node, providing various details such as Device ID, App EUI, and Dev EUI. These codes are unique and cannot be duplicated, ensuring the security of the connection and data transmission. Additionally, the dashboard shows GPS data, which sends the payload in the form of latitude and longitude, and displays a map that can be easily viewed on the dashboard show in the Figure 4.2.

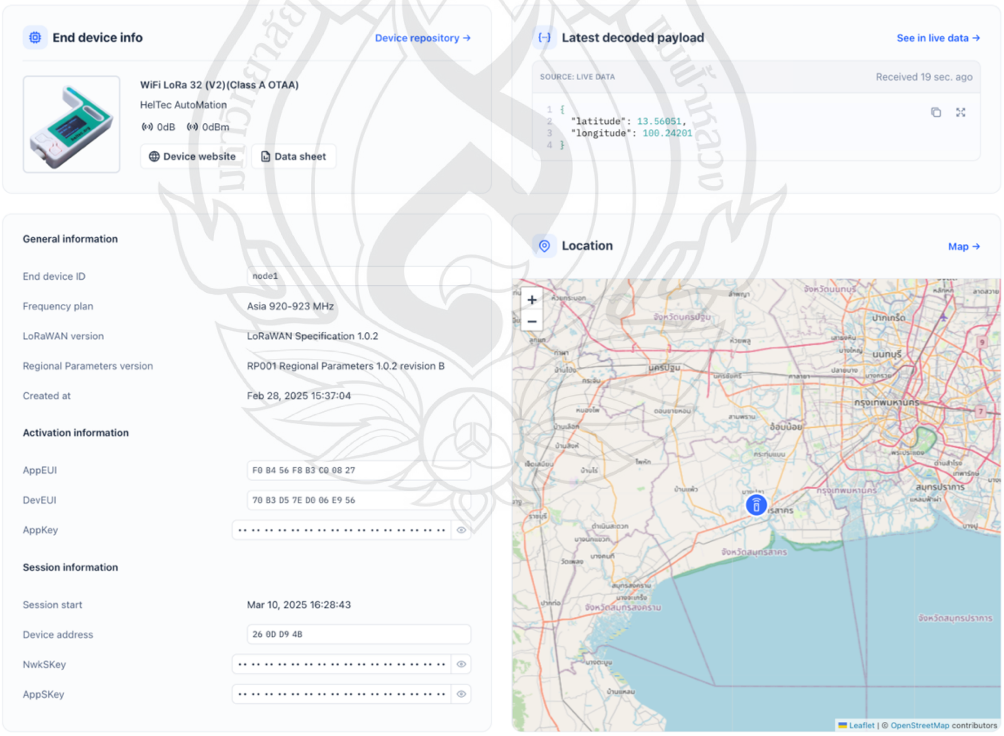


Figure 4.2 TTN Dashboard

Figure 4.3, This log page displays the uplink data from the End Node, which transmits the GPS payload. It can be observed that the transmitted data is decoded and displayed as real-time latitude and longitude (Lat, Long). This is possible because the backend performs decoding, converting the 16-character hexadecimal data set, which is shown in Figure 4.6

Figure 4.3 End node log

The positions of all tracking devices or End Nodes can be viewed on the dashboard, as shown in the Figure 4.4. Therefore, if there are multiple devices or more than two, their positions can be monitored from this single page.

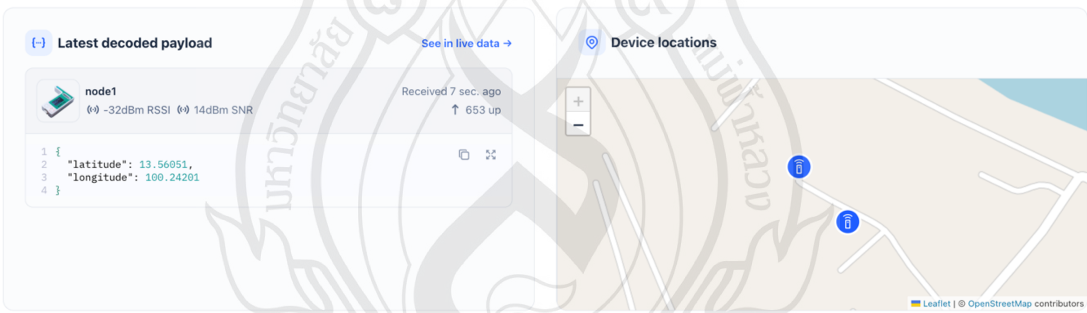


Figure 4.4 End node location

Figure 4.5, Shows the End devices page used to monitor the status of connected End Nodes. It displays two devices, node1 and node2 (used in this experiment), along with their latest activity status, indicating whether the devices are online. This allows users to easily monitor and manage all devices from a single dashboard.

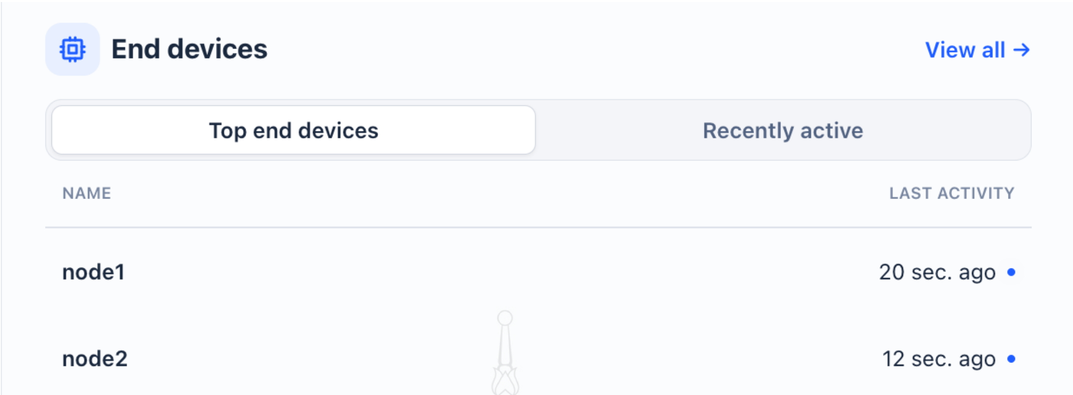


Figure 4.5 End node list

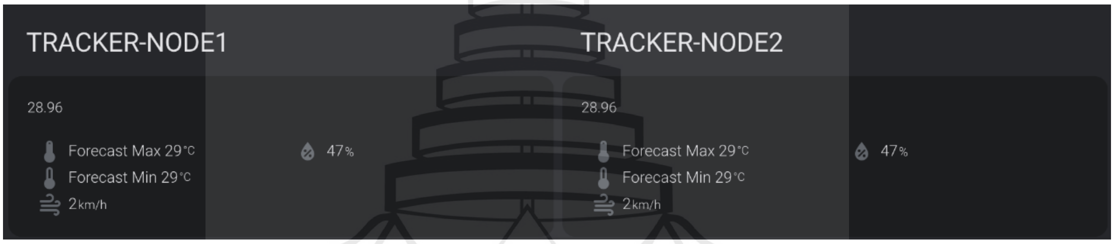


Figure 4.6 Home Assistant dashboard

Figure 4.6, This interface represents a third-party dashboard provided by Home Assistant, which allows users to customize the dashboard according to their requirements. The dashboard displays data from Tracker Node 1 and Tracker Node 2. As shown in the figure, the information includes temperature, humidity, and wind speed. These data are retrieved from the OpenWeather API, and the displayed values are referenced based on the actual geographical location of each tracker node, reflecting the real environmental conditions at those locations.

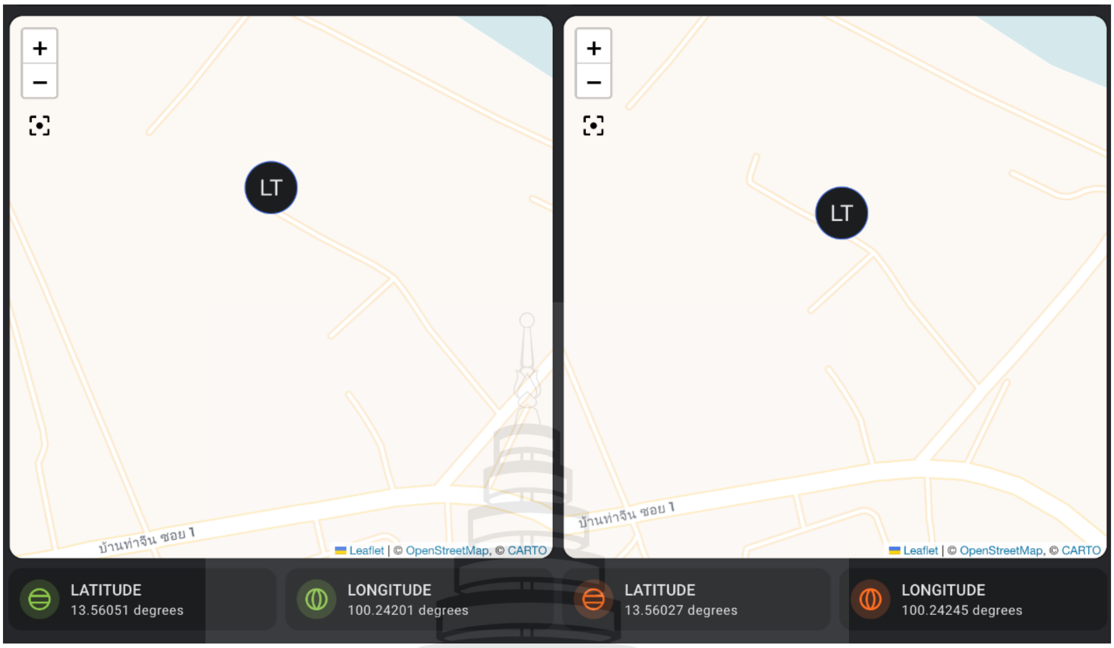


Figure 4.7 Heat map on Home Assistant dashboard

Figure 4.7, Presents a dashboard that displays the real-time map locations of the tracker devices. The latitude and longitude values are transmitted via MQTT payloads and shown on the map. The map interface supports free panning and zooming, as well as route direction functionality for navigation to the destination. In this example, the figure illustrates two tracker devices positioned approximately 30 meters apart.

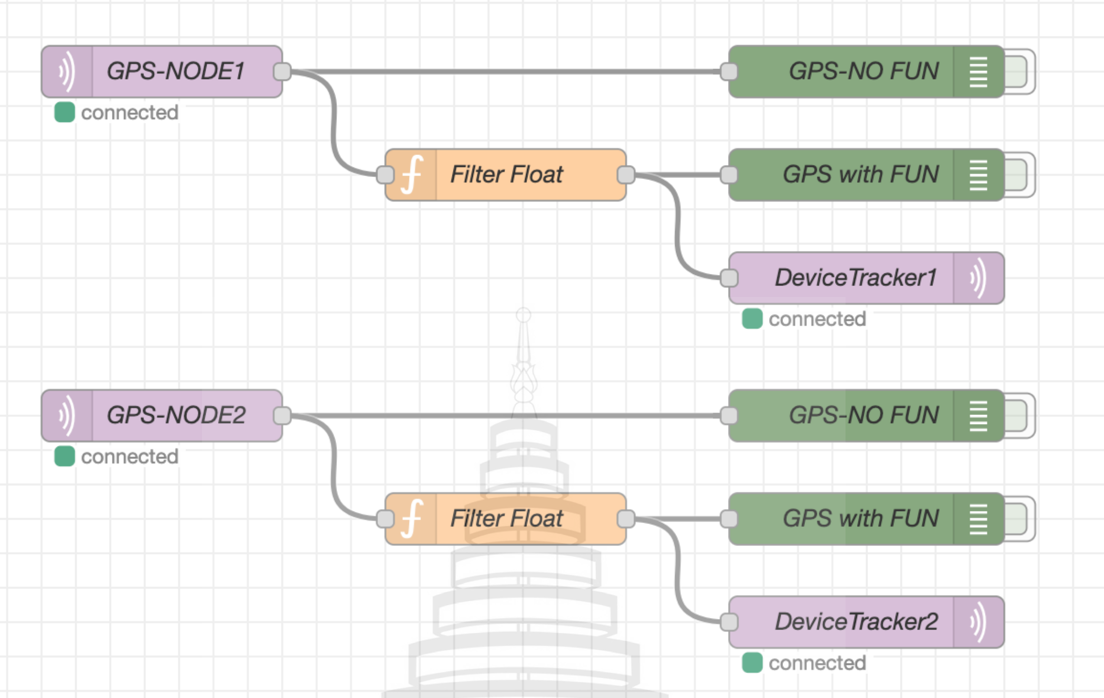


Figure 4.8 Workflow Diagram

Figure 4.8, Shows workflow diagram illustrates the process of receiving and processing location coordinate data from two GPS devices using the Node-RED platform. Initially, raw data are received through GPS-NODE1 and GPS-NODE2, which collect data from the network. The data are then forwarded through two separate paths. The first path sends the raw data directly to the GPS-NO FUN node for inspection or comparison prior to processing. The second path forwards the data to the Filter Float node, which validates and filters the latitude and longitude values to ensure they are in the correct numerical format before restructuring the data for further use. After processing, the filtered data are sent to the GPS with FUN node for visualization and then forwarded to DeviceTracker1 and DeviceTracker2, which are connected to the tracking system for real-time device location monitoring.

```javascript
const ttsPayload = msg.payload;
if (
    ttsPayload &&
    ttsPayload.uplink_message &&
    ttsPayload.uplink_message.decoded_payload
) {
    const decoded = ttsPayload.uplink_message.decoded_payload;
    const latitude = decoded.latitude;
    const longitude = decoded.longitude;
    if (typeof latitude === 'number' && typeof longitude === 'number') {
        msg.payload = {
            "latitude": latitude,
            "longitude": longitude,
            "source_type": "gps"
        };
        return msg;
    } else {
        node.warn("Latitude or Longitude is not a valid number.");
        return null;
    }
} else {
    node.warn("Invalid The Things Stack uplink payload structure.");
    return null;
}
```

Figure 4.9 Payload code for uplink message

This code show in Figure 4.9 is responsible for validating and processing data received from The Things Stack (TTS*)*, which are delivered in the form of msg.payload within the Node-RED environment. The process begins by verifying whether the received data contain the required structure, specifically the presence of uplink_message and decoded_payload. The code then extracts the geographical coordinates, namely latitude and longitude, from the decoded data and checks whether the values are of numeric type to prevent errors during further processing. If the data are valid, the payload is reformatted to include latitude, longitude, and a source_type variable, which identifies the data source as GPS data, before forwarding it to the next stage of the workflow. In cases where the data are invalid or incomplete, the code terminates execution and generates an error message to assist developers in efficiently identifying and resolving issues.

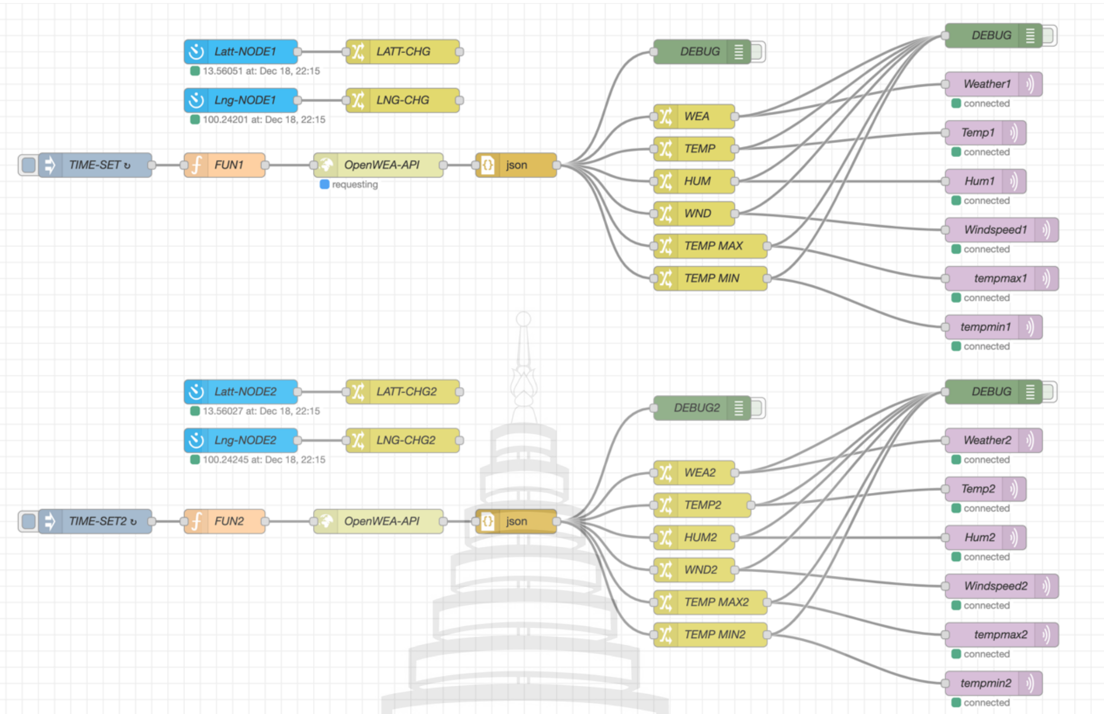


Figure 4.10 Node red flow weather data

Figure 4.10, Shows a Node-RED flow designed to retrieve and process weather data from the OpenWeatherMap API using location coordinates (latitude and longitude) from two GPS devices. The process starts by receiving latitude and longitude values from the Lat-NODE and Lng-NODE of each device. These coordinates are then adjusted and prepared using function nodes (LATT-CHG, LNG-CHG, FUN1, and FUN2) to make them ready for API requests. At scheduled times defined by the timer nodes (TIME-SET and TIME-SET2), the system sends requests to the OpenWeatherMap API through the OpenWEA-API node. The response, which is in JSON format, is parsed using the JSON node. After that, the weather data are separated into different parts, including general weather conditions, temperature, humidity, wind speed, maximum temperature, and minimum temperature. These processed data are checked using DEBUG nodes and sent to the destination system, such as a dashboard or other connected devices, for display and further use.

```
const lat = global.get("latitude");
const lon = global.get("longtitude");


const appid = global.get("openWeatherApiKey") || "520529dceda56508f74d6d29f698bc41";

if (lat !== undefined && lon !== undefined) {

    msg.url = `https://api.openweathermap.org/data/2.5/weather?lat=${lat}&lon=${lon}&appid=${appid}


    return msg;

} else {
    node.error("global.lat or global.lng is not set. Flow stopped.", msg);
    return null;
}
```

Figure 4.11 Request API from open weather

This code is used to create a request for the OpenWeatherMap API by using location data stored in global variables in the Node-RED system shows in Figure 4.11 First, the latitude and longitude values are retrieved using the global.get() function. The API key (appid) is then set by using a global variable if it is already available, or a default value defined in the code. Next, the code checks whether the latitude and longitude values are not undefined to confirm that valid location data are available. If the data are valid, the URL for the OpenWeatherMap API request is created by combining the coordinates and the API key, and the URL is assigned to msg.url to be sent to the next node for the actual API request. If the location data are missing or invalid, the code stops working and displays an error message to prevent sending incomplete requests, which helps improve the reliability of weather data retrieval based on GPS locations.

This code defines the decode Uplink function show in Figure 4.12, which decodes location data from a payload received from an End Node in a LoRaWAN system. It first checks whether the received data has a sufficient length (at least 8 bytes). Then, it extracts the first 4 bytes to compute the latitude and the next 4 bytes to compute the longitude using bitwise operations to combine the bytes into integer values. These values are then divided by 100,000 (1e5) to convert them into the correct coordinate format. Finally, the function returns the decoded latitude and longitude in a JSON format, which can be used for display or further processing in IoT systems or dashboards.

```
function decodeUplink(input) {
    var bytes = input.bytes;
    if (bytes.length < 8) {
      return {
        errors: ["Not enough bytes. Expected
8."]  };
    }
    var rawLat = (bytes[0] << 24) |
                 (bytes[1] << 16) |
                 (bytes[2] << 8)  |
                 (bytes[3]);
    var rawLon = (bytes[4] << 24) |
                 (bytes[5] << 16) |
                 (bytes[6] << 8)  |
                 (bytes[7]);
    var lat = rawLat / 1e5;
    var lon = rawLon / 1e5;
    return {
      data: {
        latitude:  lat,
        longitude: lon
      }
    };
  }
```

Figure 4.12 Decode uplink

Finally, the experimental results show that the developed LoRa Gateway can reliably connect to the network without any data loss. The data from the End Node was successfully transmitted to The Things Stack and accurately displayed on the dashboard. Additionally, the GPS payload was correctly decoded, enabling efficient real-time tracking of device location and status.

4.2 Evaluation

4.1.1 RSSI and data transmission stability: The received RSSI remained within the LoRa device sensitivity range (approximately −139 dBm), ensuring stable communication without packet loss.

4.1.2 Payload size and Spreading Factors: The payload size is 8 bytes, consisting of 4 bytes for latitude and 4 bytes for longitude. Due to its small size, the transmission does not encounter issues related to data rate or payload capacity limits. For transmission using a 125 kHz bandwidth with spreading factors SF7–SF12, providing efficient data transfer.

4.1.3 Connectivity and communication: The End Node maintained continuous connectivity, and all uplink messages were successfully received, confirming reliable system operation.

4.1.4 Distance for communication: The maximum distance achieved in this experiment was 11 km under relatively flat terrain with minor obstructions, while all transmitted packets were successfully received without loss.

4.3 The Debugging Code Result

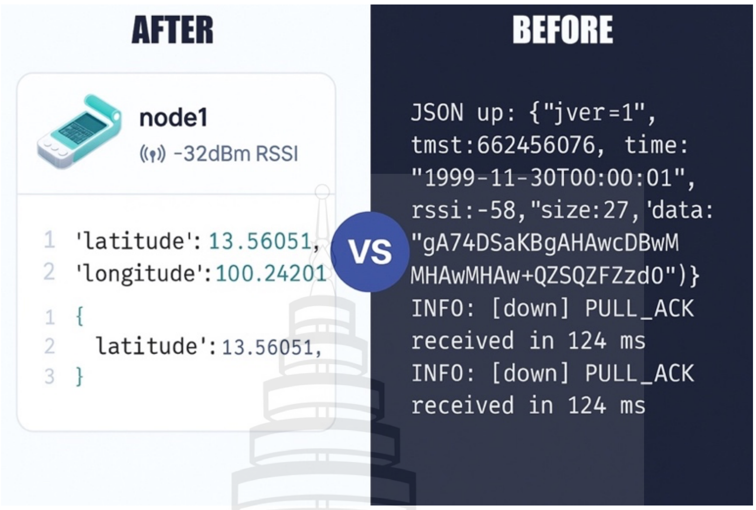


Figure 4.13 Debugging code

Figure 4.13, Shows the "Before" stage, the data received from the End Node via the LoRaWAN network is in an encoded payload format, which cannot be read or directly used. In contrast, the "After" stage presents the decoded result, which clearly shows the latitude and longitude information. This transformation allows the data to be easily interpreted and utilized for further applications, such as displaying the location on a map or performing spatial data analysis.

4.4 Distance Experiment Result

Table 4.1 Communication Experiment Result

Distance(km)	RSSI(dBm)	Spreading Factor	BW(kHz)	Payload Size(bytes)	Packet Status
5	-110	SF12	125	8	Success
5.56	-113	SF12	125	8	Success
6	-116	SF12	125	8	Success
6.64	-119	SF12	125	8	Success
7	-125	SF12	125	8	Success
8	-134	SF12	125	8	Success
9	-136	SF12	125	8	Success
9.53	-136	SF12	125	8	Success
11	-139	SF12	125	8	Success
12	-142	SF12	125	8	Lost

Table 4.1, show Total of 500 transmission and reception tests were conducted, and the results are summarized in the following table. The gateway antenna was installed on a rooftop at a height of approximately 4–5 meters, while the end device was gradually moved farther away. The testing environment remained relatively consistent, with occasional building obstructions in certain directions. The table presents results from distances of 5 km up to 11 km. Beyond this range, the signal was lost due to increased obstructions and limitations in positioning the end device, resulting in a maximum reliable testing distance of 11 km.

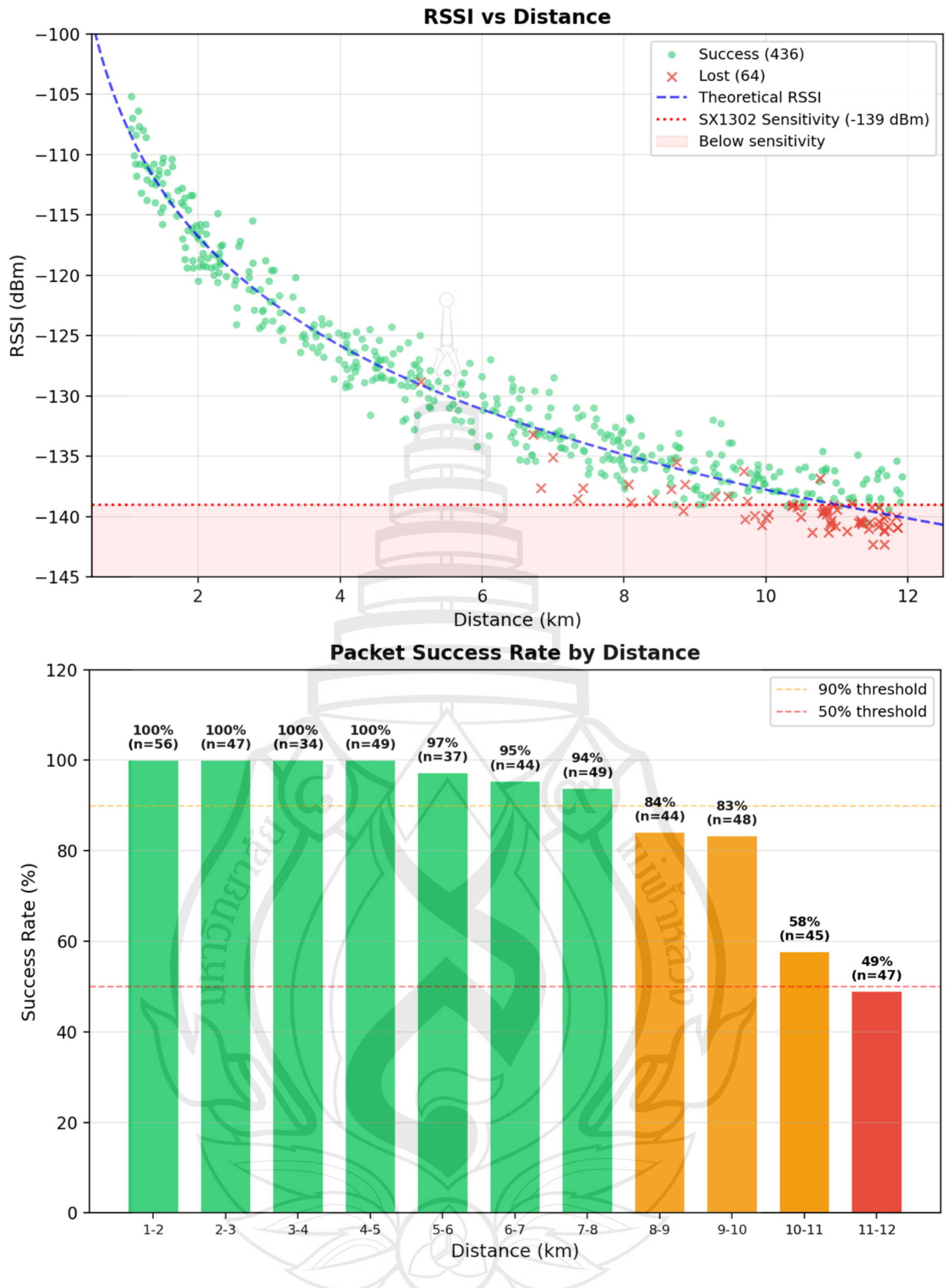


Figure 4.14 Experimental Results Graph

Figure 4.14, Graph illustrates the relationship between RSSI and transmission distance based on 500 transmission trials over a range of 1 to 12 km, using SF12 with a bandwidth of 125 kHz. The results represent a typical outdoor or semi-rural environment. At distances of 1–4 km, the RSSI ranges from approximately −105 to

−125 dBm, which is above the sensitivity threshold of the SX1302 (−139 dBm), resulting in a 100% packet success rate.

As the distance increases to 7 km, the RSSI decreases to around −133 dBm, with a success rate of 98%, indicating reliable communication. Beyond 7 km, the RSSI approaches the sensitivity limit, causing the success rate to decrease to 87% within the 7–10 km range, and dropping significantly to 53% at distances of 10–12 km, where many signals fall below the demodulation threshold.

At 12 km, the RSSI reaches approximately −140 dBm, exceeding the receiver sensitivity limit, resulting in complete signal loss and a 0% success rate. These results confirm that the DIY LoRaWAN gateway can provide reliable communication (greater than 90% success rate) up to approximately 10 km, with a maximum operational range of around 10–11 km under SF12 configuration.

4.5 Comparing Experimental Results

Table 4.2 Experimental results of P2P and LoRaWAN Protocol

Distance	P2P Success Rate	LoRaWAN Success Rate
1 - 4 km	80 – 100%	100%
4 - 5 km	50 – 70%	100%
5 – 6 km	0%	97%
6 – 12 km	0%	95% - 49%

Table 4.2, The experimental results from 500 transmission trials demonstrate a clear advantage of the LoRaWAN gateway over the LoRa P2P system. At distances of 1–4 km, both systems perform well, with the LoRaWAN gateway maintaining a 100% success rate.

A significant difference is observed beyond 5 km, where the P2P system completely loses communication (0% success rate) due to the sensitivity limitation of the SX1276 at −120 dBm. In contrast, the LoRaWAN gateway, with a sensitivity of −139 dBm, maintains a success rate of 97% at 5–6 km, 94% at 7–8 km, 83% at 9–10 km, and 58% at 10–11 km.

Overall, the LoRaWAN gateway provides approximately twice the effective communication range of the P2P system and continues to operate reliably within the 5–10 km range, where the P2P system is no longer functional.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Discussion

The experimental results from developing a low-cost LoRaWAN Gateway using Raspberry Pi 4, LR1302, and The Things Stack indicate that the system successfully meets its primary objectives, particularly in connection stability, device scalability, and accuracy of GPS location decoding.

5.1.1 Stability of Connection

Testing demonstrated highly stable connections between the End Node and the Gateway, with no observed packet loss. The continuous transmission of data was confirmed by a consistently increasing Frame Counter, validating the reliability and efficiency of the system in practical use.

5.1.2 Accuracy of GPS Coordinate Decoding

The system accurately decoded GPS data from the LoRaWAN Payload using a fixed-point encoding method that scaled location data efficiently to conserve payload size. Bitwise operations effectively transformed payload data into correct latitude and longitude coordinates, aligning with common practices in Cayenne LPP standards.

The experiment showed positional accuracy within ±5 to ±10 meters under open-sky conditions, aligning with previous research, such as wildlife tracking studies that reported horizontal errors averaging ±4.7 meters (with a standard deviation of ±3.9 meters), and commercial GPS trackers typically offering accuracy within ±2.5 to ±10 meters.

However, accuracy significantly degraded in environments with substantial obstructions, such as dense urban areas or heavily wooded regions, potentially increasing positional error to ±20-30 meters or more. Factors influencing accuracy include hardware quality, GNSS operational modes, payload encoding methods, and environmental conditions.

Compared to commercial GPS trackers using GSM or GPS-only technologies, the positional accuracy was similar. The main advantage of the LoRaWAN-based system lies in lower costs, reduced power consumption, and suitability for applications that do not require continuous real-time tracking.

5.1.3 Dashboard Data Visualization

The dashboard integrated with The Things Stack effectively displayed real-time GPS positions and device statuses clearly, allowing users to manage multiple devices conveniently from a single interface.

5.2 System Limitations

Key limitations identified include restricted transmission range in urban settings and dependency on continuous power supply and stable internet connectivity for Gateway operation.

5.3 Conclusion

This thesis presents the design, development, and performance evaluation of a low-cost location tracking system based on LoRaWAN technology. The system was developed using a Raspberry Pi 4 together with an LR1302 LoRa gateway module, and The Things Stack platform was used as the network server. Experimental results show that the developed system can transmit data from end devices to the gateway in a stable manner, with no packet loss observed during the testing period. This demonstrates the reliability of uplink communication in the proposed system.

The performance evaluation results indicate that the received signal strength values are within the usable sensitivity range of LoRa devices. The communication parameters, including a bandwidth of 125 kHz and spreading factors ranging from SF7 to SF12, are suitable for long-range data transmission under low power consumption conditions. In addition, the connectivity of the end devices was verified through continuously increasing frame counter values, confirming that uplink data transmission was successfully maintained throughout the experiment.

Furthermore, the encryption and decryption processes of the LoRaWAN payload function correctly. The received payload data can be accurately decoded into latitude and longitude coordinates obtained from the GPS. As a result, real-time location information can be displayed on the system dashboard. In open-area environments, the system provides location accuracy within approximately ±5 to ±10 meters. However, in environments with obstacles or high levels of interference, such as dense urban areas or areas with heavy vegetation, the location accuracy tends to decrease to approximately ±20 to ±30 meters. Additionally, the dashboard can display data in integration with third-party platforms, such as Home Assistant, via the MQTT protocol, which makes device location tracking more convenient for users.

In conclusion, the proposed low-cost LoRaWAN gateway system is suitable for low-power, long-range location tracking applications, especially for use cases that do not require continuous real-time tracking. The system shows potential for practical applications, such as tracking lost children, elderly individuals, or valuable assets in relatively simple environments. However, the system still has limitations in terms of location accuracy in complex environments. Therefore, future research should focus on improving location accuracy, enhancing energy efficiency, and extending system capabilities to support broader application scenarios.

5.4 Publication

(1) N. Jengsriwong and S. Chansareewittaya, "LoRaWAN GPS Tracker," 2023 Joint International Conference on Digital Arts, Media and Technology with ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI DAMT & NCON), Phuket, Thailand, 2023, pp. 199-202, doi: 10.1109/ECTIDAMTNCON57770.2023.10139617.

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