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Store and Forward CubeSat using LoRa Technology and Private LoRaWAN-Server

Parinya Anantachaisilp, Marut Muangkham, Nuttawat Punpigul, and Mason Thammawichai
Department of Electrical Engineering, Navaminda Kasatriyadhiraj Royal Air Force Academy, Bangkok, Thailand
Phone: (66)870047363, Email:parinya_a@rtaf.mi.th

ABSTRACT

In the THAIIOT project, we built a 3U CubeSat with LoRa module and private LoRaWAN-server payload. The main goal of this project was to develop the payload for CubeSat in the low-earth orbit to receive uplink data via LoRa technology between LoRa module and private LoRaWAN-server on CubeSat to store data and then use S-band transceiver to downlink the data to ground station. In addition, we improved network security between ground LoRa nodes and the private LoRaWAN-server by using Advanced Encryption Standard (AES). In this paper, we present the efficiency of THAIIOT payload, focusing on store and forward data via LoRa technology. From the calculation results, the calculated link budget showed that the LoRa technology can transmit and receive data at a distance up to 2000 km. By assuming the transmitted data size of 35 bytes, the possible maximum data rate was 292 bps, which required 1.81 s of Time on Air (ToA). Moreover, the experimental results verify the capability of the THAIIOT payload to successfully transmit the data up to 2,200 km.

INTRODUCTION

Nowadays, the Internet of Things (IoT) devices widely used across the world where the internet network is available, however it has not yet achieved global coverage, especially in the mountains, deserts, forests and over the sea. In these remote areas, satellite communication is used instead. The satellites used for the IoT network are normally launch to the Low Earth Orbit (LEO) where the altitude from the earth is less than 1,000 km. The key advantages of the LEO satellites are the capability to transmit the data with smaller delay, the low transmission power losses, and the higher frequency to orbit around the world. Moreover, the constellation of this kind of satellite increases the continuation of the communication between satellites and ground stations. In some cases, the design objective of the constellation is to have the near real-time satellite communication.

With the trend in a LEO small satellite constellation for IoT application, there are several companies and research groups try to launch these satellites in a few years. The concept of operation for the IoT satellite can be divided to two formats. The first format is the transmission of the data from the end devices to small satellite constellation and then forward to the geostationary satellite, which has more power to transmit data at higher rate. The geostationary satellite then send the data to the ground server before distribute to the subscribed users. The IoT satellites in the first format are mainly for commercial purpose such as Aprizesat [1] and LituanicaSAT-2 [2]. The second format is the transmission of the data from end devices to store in the all satellites of the constellation and directly forward to the ground station. Most of the second format constellation for the commercial use requires a lot of satellites ranging from 40 – 200 satellites such as Sky and Space Global [3], Astrocast [4-5], SpaceBee [6], and LacunaSat [7-8].

One of the important technologies for the IoT satellite is the low power and long range transceiver. This will enhance the efficiency of the end devices connected to the satellites. For instance, the TRICOM-1R [9], the 3U cubesat of University of Tokyo develop the low power and long range transceiver based on the LoRa technology manufactured by Semtech Corporation. However, the previous design of TRICOM-1R is limited to one to one communication between end device and gateway on the satellite. In order to increase the number of end devices communicate to the satellite and to increase the security of the communication network. The multiple to one communication between end devices and the satellite gateway must be studied and designed. Therefore, the THAIIOT Project by Navaminda Kasatriyadhiraj Royal Air Force Academy, Thailand, was initiated to solve this problem by having this payload in the 3U cubesat.

The remainder of this paper is organized as follows. First, a brief overview of THAIIOT cubesat will be explained. The next section describes relevant information of the store and forward payload including LoRa Technology and Private LoRaWAN-Server. After that the experimental setup and results are illustrated to verify the capability of the payload as calculated in the previous section. Lastly, the conclusion of the study is drawn in the last section.

OVERVIEW OF THAIIOT CUBESAT

The THAIIOT cubesat is developed for the IoT network purpose. The sensor data from each end devices on ground will be send to and stored on the satellite gateway. Then stored sensor data is forwarded to the ground station for the analysis as illustrated in Figure 1.

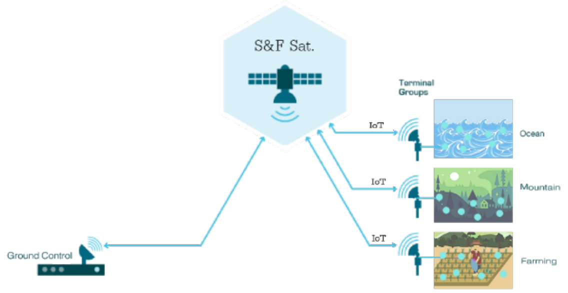

Figure 1: THAIIOT Mission

This satellite will be in low earth orbit at about 600 km altitude. The following are the planned missions of the THAIIOT cubesat:

- The cubesat can provide IoT service for all area of Thailand

- End devices can transmit data to the cubesat up to 2000 km

- End devices consume low power and last for 3-5 years with battery energy

- The cubesat can receive data from end devices up to 50 units simultaneously

- The uplink transmission uses the Low Power Wide Area Network (LPWAN) technology and the downlink transmission uses the S-band transmitter for high data rate.

The THAIIOT cubesat consists of 6 subsystems including communication (COMM), command and data handling (CDH), payload (PL), electrical power system (EPS), attitude determination and control system (ADCS), and structure (STR) as shown in Figure 2. The cubesat uses VHF to receive uplink command from ground station and uses UHF to send the beacon and telemetry to the ground station. Moreover, the stored sensors data are sent by the S-band transmitter. The cubesat is designed to do nadir pointing during the mission mode by using one reaction wheel and three magnet torquers as actuators. The payload subsystem consists of the LoRa gateway that can store the data received from end devices on the ground and forward the data to the ground station which is main mission of THAIIOT cubesat.

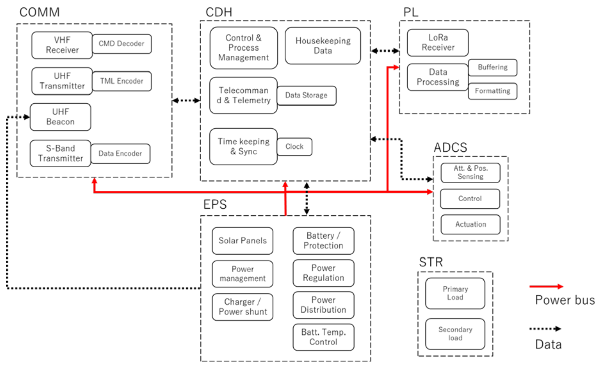

Figure 2: THAIIOT Subsystems

The mission operation mode starts from checking the availability of the data. If there is some data in the payload subsystem, the CDH subsystem will send command to stop sending the beacon and activate the LoRa receiver in order to receive data from end devices for some specified time period. After that, the LoRa receiver will be turned off and the telemetry data will sent through the UHF transmitter. Then the S-band transmitter is activated and ready to send payload data. If the payload data does not transmit successfully, the microcontroller of the transmitter will resend until completion. After all data is sent, the cubesat will enter Safe Mode and prepare for the next mode. The flow chart of the mission mode is shown in Figure 3.

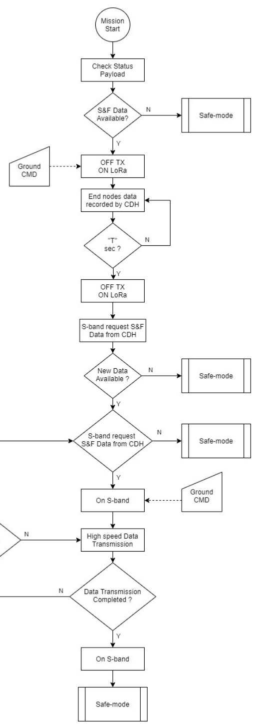

Figure 3: Mission Operation Mode

STORE AND FORWARD PAYLOAD

In order to meet the required store and forward mission of the THAIIOT cubesat, the Low Power Wide Area Network (LPWAN) is selected due to its low power consumption and wide area coverage [10]. LPWAN technology has an important role in the connectivity of devices with small amount of the transmitted data. It can operate continuously with very little power consumption which is suitable for the IoT application. Moreover, LPWAN can also extend the range of the communication. The advantages of LPWAN over other communication methods in terms of range and power consumption are illustrated in Figure 4.

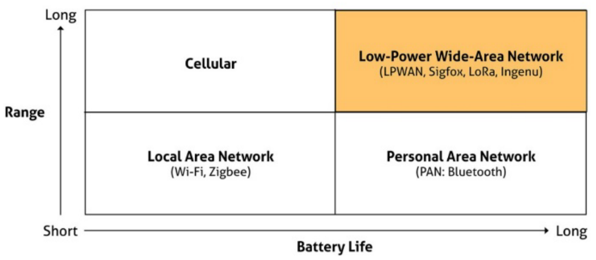

Figure 4: Comparison of communication methods [11]

LPWAN technology has been developed for the commercial purpose by several companies such as Long Term Evolution for Machine Type Commutation (LTE-M), Narrow Band IoT (NB-IoT), SigFox (SigFox), and Long Range (LoRa). All of the mentioned technology are capable of long range communication and consume less energy. However, each company has different approach technique to operate the LPWAN depending on the business model. Table 1 shows the comparison of each technology [12]. From Table 1, it shows several advantages of LoRaWAN over other technologies as follows.

- Data rate is ranging from 290 bps to 50 kbps at 125 kHz which requires shorter Time-on-Air
- It consumes the least energy
- The Chirp Spread Spectrum (CSS) modulation can transmit at the level lower than noise floor
- The data can be encrypted both on public and private network
- The data rate is adaptive
- LoRaWAN can be use freely without any subscription

From all above advantages, LoRaWAN is selected as the technology to develop the payload gateway and end devices for THAIIOT project.

Table 1. Comparison of LPWAN technology [3]

Feature	LoRaWAN	Sigfox	NB-IoT	LTE-M
Modulation	SS Chirp	GFSK/ DBPSK	UNB/ GFSK/ BPSK	OFDMA
Data Rate	290 bps – 50 kbps	100 bps 12/8 bytes Max	100 bps 12/8 bytes Max	200 kbps – 1 Mbps
Link Budget	154 dB	146 dB	151 dB	146 dB
Battery lifetime	8 – 10 years	7 – 8 years	7 – 8 years	1 – 2 years
Power Efficiency	Very High	Very High	Very High	Medium
Security/ Authentication	Yes (32 bits)	Yes (16 bits)	No	Yes (32 bits)
Range	2 – 5 km urban 15 km suburban 45 km rural	3 – 10 km urban - 30 – 50 km rural	1.5 km urban - 20 – 40 km rural	35 km – 2G 200 km – 3G 200 km – 4G
Interference Immunity	Very High	Low	Low	Medium
Scalability	Yes	Yes	Yes	Yes
Mobility/ Localization	Yes	No	Limited, No Loc	Only Mobility

Basic LoRa Theory

This section shows the data structure and message format of LoRaWAN which is used within this project. From the information of structure and format of data shown in Figure 5-7, per 1 packet uplink, there are 8 symbols of preamble, 19 bytes of Header, and maximum of 242 bytes of payload data. In addition, Table 2 shows the amount of data in the format of LoRa packet of some sensor types assuming that GPS data is included in every sensor.

There are 3 important parameters of the LoRa module that need to be calculated to ensure the mission requirements are met which are including time on air, data bit rate, and link budget.

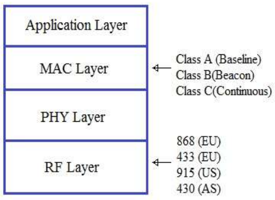

Figure 5: LoRa Protocol Stack [12]

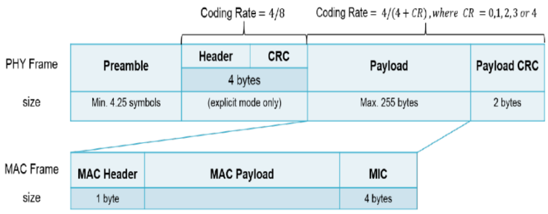

Figure 6: LoRa Packet Structure [12]

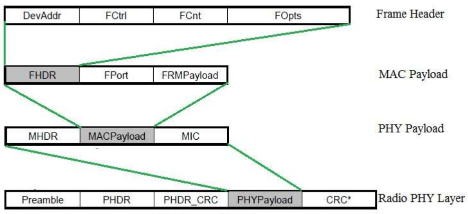

Figure 7: LoRa Message Format [12]

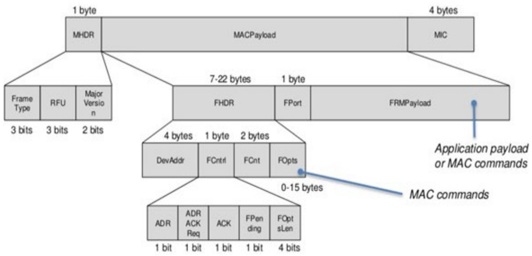

Figure 8: MAC Layer [12]

Time on Air (ToA) can be calculated as shown in Eq. (1) [13]

$$ToA\,[s] = T_{preamble} + T_{payload} \quad (1)$$

where

$$T_{preamble}[s] = (n_{preamble} + 4.25)T_s \quad (2)$$

$n_{preamble}$ is the number of Preamble [symbol]

$$T_s[s] = \frac{2^{SF}}{BW} \quad (3)$$

SF is the Spreading Factor ranging from 7-12

Table 2. Total data of different sensor types (Uplink)

Sensor	Preamble (Symbols)	Sensor Data (Bytes)	GPS Data (Bytes)	MAC Payload (Bytes)	Payload CRC (Bytes)	Total of Payload Data (Bytes)
Thermo Hydro	8	4	8	17	2	31
Rain	8	3	8	17	2	30
UV index	8	5	8	17	2	32
Soil Moisture	8	1.5	8	17	2	28.5
Wind Speed	8	1	8	17	2	28
Wind Direction	8	1	8	17	2	28

BW is the bandwidth [Hz]

$$T_{payload}[s] = \left(8 + \left(ceil\left(\frac{8PL-4SF+28+16CRC-20H}{4(SF-2DE)}\right)(CR+4)\right)\right)T_s \quad (4)$$

PL is the amount of Payload [Byte]

CRC is the Cyclic Redundancy Checksum [1: enable, 0: disable]

H (Header) default=0 [0: enable, 1: disabled]

DE (Low Data Rate Optimize) default=1 [1: enable, 0: disabled]

CR (Coding Rate) is the ratio of sent data and checked data. The value is ranging from 1-4

With the provided equation to calculate time on air, it can be seen that coding rate in Figure 9. In addition, LoRa data rate can be calculated by Eq. (5)

$$R_b[bps] = SF * \frac{\frac{4}{4+CR}}{\frac{2^{SF}}{BW}} * 1000 \quad (5)$$

where R_b is Transmission bit rate [bps]

From the specified mission, we want to have the transmission distance as far as possible. The value of SF for all calculation must be 12. While the value of CR depends on the transmission environment. From Table 3, it shows that the highest bit rate for LoRa is 292 bps.

Link Budget

LoRa link Budget is the sum of the gains and losses that occur while data transmits from the transmission sector through the medium to the receiving sector. The amount that affects the LoRa link Budget, which is the power used to transmit and the LoRa receiver sensitivity that specifically for each chip. In link budget calculation, the important factor is fade margin. It must be over 3 dB. Link budget for this project illustrate in the Appendix A.

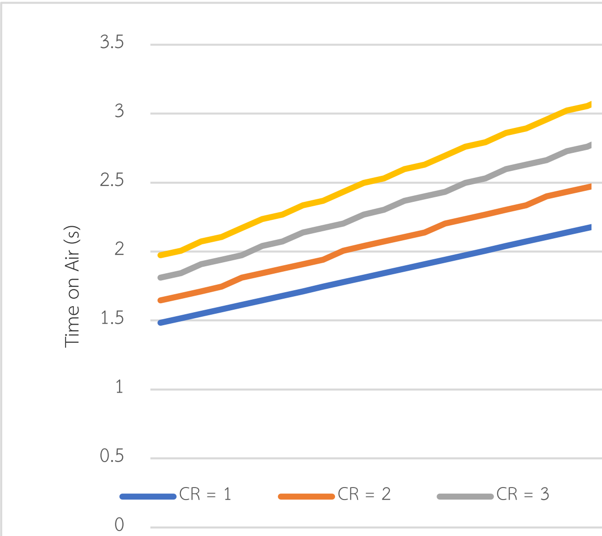

Figure 9: Time on air of data at different coding rate

Table 3: LoRa Data Bit Rate

Spreading Factor	Coding Rate	Bandwidth (kHz)	LoRa Data Rate (bps)
12	1	125	292
12	2	125	244
12	3	125	209
12	4	125	183

LoRaWAN structure

LoRa technology has its own network structure called LoRaWAN. There are 4 components in LoRaWAN including end device, gateway, network server, and Application Server.

End device: It is the data transfer device that using the LoRa modulation technique to modulate the data signal then send it through the air to LoRa gateways

Gateway: It is the medium device between End-device and Network service. Generally, Gateway will send data received from End-device to Network service using internet. Gateway is also the point to schedule the Downlink signal coming from Network service to send to the End device.

Network Service: It is the LoRaWAN main network, is responsible for collecting and sorting data from all gateways. It also decodes the received data before forwarding to the Application Server via the internet. The network service usually in the form of a Cloud system so that the users can access to the network anywhere there is internet.

Application Server: It is the user interface software, using the Network service API to control Network service or Downlink data to End-device. Application Server usually installs with Network service for easy and fast data transfer.

Typically, LoRaWAN is designed for the terrestrial communication, but we want to make use of this technology for satellite communication. Therefore, we have to modify some structure of the LoRaWAN. Figure 10 shows the LoRaWAN structure for terrestrial communication where the communication between end devices and gateway use CSS protocol and the rest use internet protocol. In the satellite application, it is quite difficult to use internet protocol, therefore, we modify the structure of the LoRaWAN for the satellite by using wires instead of internet protocol as shown in Figure 11.

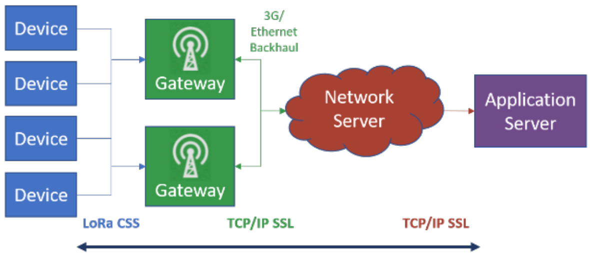

Figure 10: LoRaWAN structure for terrestrial communication

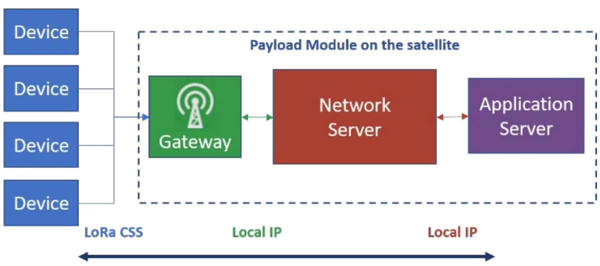

Figure 11: LoRaWAN structure for satellite communication

Hardware Structure

The hardware structure design of the payload subsystem can be divided to 2 parts. The first one is the hardware structure of the gateway. From the gateway connection diagram as shown in Figure 12, there two main modules that connect to the subsystem from outside (grey dashed box). The first one is the EPS module which provide the power to the payload subsystem. The second is the main bus where all data is passed through this module. For our design within the payload module, it consists of the main system board and the back-up system board. The details of both systems are the following.

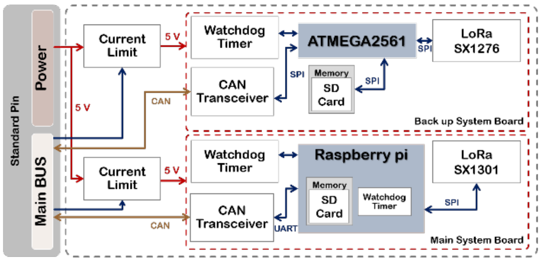

Figure 12: Gateway connection diagram

- Current limit: it controls the amount of electrical current to the payload module. The current range is from4.5-5.5 V. Moreover, it will prevent short circuit and single event latch up.

- Watchdog Timer: it checks the status of the all connected components to the module. If some components is stuck longer than specified and cannot send signal to reset the watchdog timer. The watchdog timer will restart that components immediately.

- CAN Transceiver: it helps to organize the communication in order send/receive command or data between modules through CAN bus.

- SD card: this card stores all received data of the payload module. There are 2 SD cards. In normal condition, only one SD card is used. The spare one will be used in the case of malfunction of the main one from single event effect.

- LoRa SX1301/ SX1276: the SX1301 is the multi-channel module where it can receive signal up to 8 channels simultaneously. The more channels the more end devices data can be received at the same time. While the SX1276 is a single-channel module that send or receive data only 1 channel at a time.

- Raspberry pi Zero: it is used as the processor of the main system. It processes the received data and stores in the SD card. The stored data is waited for the command from CDH subsystem to send data out through CAN bus. Note that the SD card and watchdog timer are built-in the Raspberry pi zero.

- ATMEGA2561: it is used as the processor of the back-up system. The processing efficiency is lower than the raspberry pi, however, the stability of this board is better. Another drawback of ATMEGA2561 is that it can work with only SX1276 LoRa module. This means that the back-up system can receive data only 1 channel at a time, but the system will be more stable due to its simplicity structure.

Even though raspberry-pi requires SD card for a data storage and operating system which tends to have more problem than ATMEGA2561 that uses flash memory during the single event effect. However, the processing efficiency of raspberry pi is much higher and flexible to use with other software. Therefore, THAIIOT project chooses raspberry pi as a main system for payload module.

The second hardware structure design is the end device. From the end device connection diagram as shown in Figure 13, the power of the module is from two Li-ion batteries connected in series. The details of the components of the end device are the following.

- Voltage Regulator: it regulates the input voltage of 8.4 V to supply components at 3.3 V and 5 V.

- Watchdog Timer: this component has the same function as in the gateway explained earlier.

- SD card: this card stores all sensor data and the communication log history between end device and gateway.

- Sensor: this component is used to measure the desired value depending on the objective such as GPS, temperature, and water level.

- LoRa SX1276: SX1276 is a single-channel module that send or receive data only 1 channel at a time. This module is used in order to minimize the power consumption.

- ATMEGA328p: it is used as a processing unit of the end device where the library for LoRa module is installed. Moreover, it will manage the sensor data that will be sent to payload module.

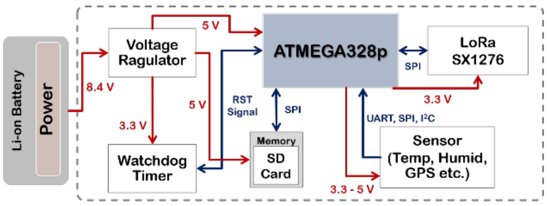

Figure 13: End device connection diagram

Software structure

The software structure design of the payload subsystem can be divided to 2 parts. The first one is the software structure of the gateway. From the gateway flow diagram as shown in Figure 14, it consists of LoRaWAN and data handling part. The LoRaWAN part will manage the transmitted data by using LoRa technology. The data handling part will manage the decrypted and filtered data from LoRaWAN part as well as control the communication between subsystems through CAN bus. The details of the components of the software for gateway are the following.

- Package forwarder: it works on the LoRa processor. This program works with the communication component of the gateway directly to send and receive data with end device.

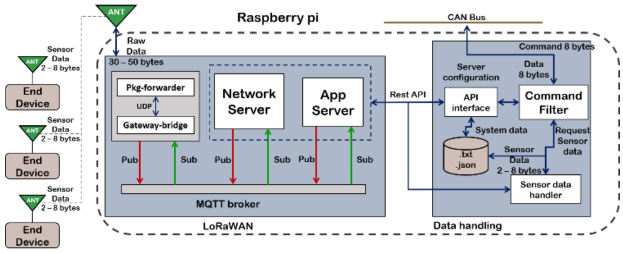

Figure 14: Gateway flow diagram

- LoRa gateway bridge: this program takes data from Package forwarder and converts to JSON object for the compatibility with the LoRa server. This object is then sent to MQTT broker.

- LoRa Network server: this program is the center of the LoRaWAN. It manages the redundant data that occurs during the transmission from gateway to server. It also organize the que of the downlink data.

- LoRa app server: this program manages the request to connect to server from end devices. It also encrypts and decrypts end devices data transferred to the server. In addition, it also connects with other program through API (RESTful, gRPC or MQTT)

- API interface: this program organizes the configuration of the server by recording the history of server and the connecting history between App server and Server config.

- Command Filter: this program receives and filters commands from other subsystems to payload subsystem through CAN bus. It also sends data from gateway to other systems through CAN bus.

- Sensor data handler: this program stores sensor data sent from end devices. The stored data will be kept in the SD card and be ready to be called from CDH module. The stored data is in the .json และ .txt.

- MQTT broker: this program is the connection between programs within the gateway.

In addition, the software for the backup system of the payload module is run by only one program. It cannot implement multiple programs simultaneously. The program will control the communication between LoRa SX1276 and end device. The sensor data from end device will be kept in the SD card and be ready to be called from CDH module. The most important part of this program is the Radiohead library that control the peer-to-peer operation of LoRa SX1276.

The second software structure design is for the end device. Since the end device uses the Atmega328p processor unit. The most important of the library of this software is LMIC library which is used for the LoRa SX1276. The rest of the needed libraries are typically for the Arduino UNO microcontroller which are easy to find and develop.

EXPERIMENTAL SETUP AND RESULTS

With the details of the design of the hardware and software of the gateway and end devices in the previous section, we have built the hardware of gateway and end devices as well as written the software for both components as shown in Figures 15 and 16, respectively. These two components are used for the experiment to verify the maximum distance of the LoRa communication. The experiment objective is to test the efficiency of the transmission of LoRa gateway and end devices by attenuating the transmitted signal from end devices to the satellite. The amount of the attenuation determines the transmission distance.

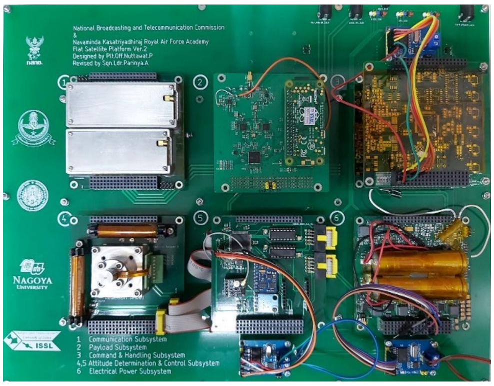

Figure 15: Payload Subsystem (number 2)

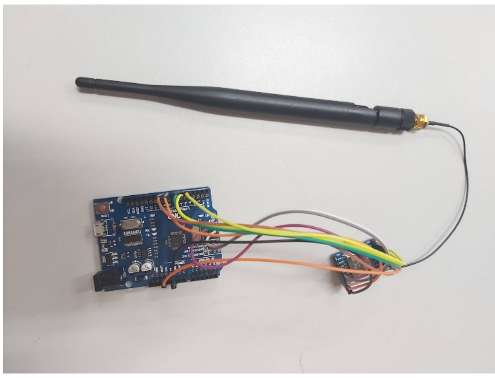

Figure 16: End Device

Experimental setup and procedure

Firstly, the power of the received signal on the gateway at different distances is calculated by using Eq. (6)

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{channel\ tx} - L_{channel\ rx} - FSL \qquad (6)$$

where

P_{tx} is transmitting power [dBm]

G_{tx} is transmission antenna gains [dBi]

G_{rx} is receive antenna gains [dBi]

$L_{cable\ tx}$ is losses from cable, connectors, branching unit Tx [dB]

$L_{cable\ rx}$ is Losses from cable, connectors, branching unit Rx [dB]

FSL is Free space loss [dB]

P_{rx} is Receive Power [dBm]

The selected frequency of the LoRa module is 433.135 MHz and the calculated received power of the gateway is summarized in Table 3.

Table 3: Calculation of received powers at gateway

Distance (km)	P_{tx}	$L_{cable\ tx}$	G_{tx}	FSL	G_{rx}	$L_{cable\ rx}$	P_{rx}
500	14	2	5	139.157	2	1	-121.157
1000	14	2	5	145.178	2	1	-127.178
1500	14	2	5	148.700	2	1	-130.7
2000	14	2	5	151.198	2	1	-133.198
2200	14	2	5	152.026	2	1	-134.026
2450	14	2	5	152.961	2	1	-134.961
2750	14	2	5	153.964	2	1	-135.964

Moreover, the experiment will use different size of the attenuator to simulate the path loss for each distance. The end device and the attenuator need to be set up in the closed environment as shown in Figures 17-19 in order to prevent the leakage of signal during the testing. The size of attenuator is calculated by using

Eq. (7) and the received power from table 3 in each distance.

$$Atteuator(dB) = P_{tx} - P_{rx} + G_{tx} + G_{rx} - L_{channel\,tx} - L_{channel\,rx} \quad (7)$$

Table 4: Calculation of attenuator

P_{tx} (dBm)	$L_{cable\,tx}$ (dB)	G_{tx} (dBi)	G_{rx} (dBi)	$L_{cable\,rx}$ (dB)	P_{rx} (dBm)	Attenuator (dB)
17	1	0	0	0	-121	137
17	1	0	0	0	-127	143
17	1	0	0	0	-130	146
17	1	0	0	0	-133	149
17	1	0	0	0	-134	150
17	1	0	0	0	-135	151
17	1	0	0	0	-136	152

Figure 17: End Device experimental set up (1)

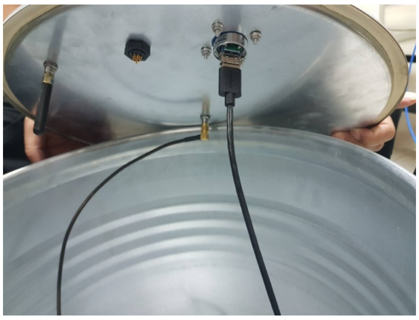

Figure 18: End Device experimental set up (2)

Figure 19: End Device experimental set up (3)

Moreover, to monitor the leakage of signal during testing, the spectrum analyzer is installed as shown in Figure 20.

Figure 20: Spectrum analyzer set up to monitor the signal leakage

Experimental results

The experiments are implemented by using 5 attenuators for 5 different transmitted distance. The first test use 137 dB attenuator to simulate the transmission of 500 km. The received power in this experiment is calculated by using Eq. (8)

Receiver Power (dBm) = RSSI + SNR (8)

The experimental results are summarized in Table 5-12

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Table 5: Experimental results when using 137 dB attenuator (500 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC passed	-112	-6.0	-118
2	CRC passed	-112	-5.5	-117.5
3	CRC passed	-113	-5.5	-118.5
4	CRC passed	-112	-5.8	-117.8
5	CRC passed	-112	-5.8	-117.8
6	CRC passed	-112	-5.5	-117.5
7	CRC passed	-112	-6.8	-118.8
8	CRC passed	-112	-5.8	-117.8
9	CRC passed	-110	-6.0	-116
10	CRC passed	-111	-6.0	-117

Table 6: Experimental results when using 143 dB attenuator (1000 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC passed	-113	-12.5	-125.5
2	CRC passed	-113	-13.2	-126.2
3	CRC passed	-113	-13.0	-126
4	CRC passed	-110	-14.2	-124.2
5	CRC passed	-112	-13.2	-125.2
6	CRC passed	-112	-13.2	-125.2
7	CRC passed	-110	-13.5	-123.5
8	CRC passed	-110	-14	-124
9	CRC passed	-112	-13.2	-125.2
10	CRC passed	-113	-13.5	-126.5

Table 7: Experimental results when using 146 dB attenuator (1500 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC passed	-111	-17.2	-128.2
2	CRC passed	-112	-17.8	-129.8
3	CRC passed	-113	-17.8	-130.8
4	CRC passed	-110	-17.2	-127.2
5	CRC passed	-112	-17.2	-129.2
6	CRC passed	-112	-17.2	-129.2
7	CRC passed	-112	-17.8	-129.8
8	CRC passed	-111	-18	-129.0
9	CRC passed	-111	-17.5	-128.5
10	CRC passed	-111	-17.2	-128.2

Table 8: Experimental results when using 149 dB attenuator (2000 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC passed	-112	-17.8	-129.8
2	CRC passed	-110	-17.0	-127
3	CRC passed	-113	-18	-131
4	CRC passed	-111	-17.2	-128.2
5	CRC passed	-110	-17.5	-127.5
6	CRC passed	-111	-17.8	-128.8
7	CRC passed	-113	-17.5	-130.5
8	CRC passed	-113	-17.8	-130.8
9	CRC passed	-112	-17.0	-129.0
10	CRC passed	-112	-17.2	-129.2

Table 9: Experimental results when using 150 dB attenuator (2200 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC passed	-112	-19.2	-131.2
2	CRC passed	-112	-19.0	-131.0
3	CRC passed	-113	-18.2	-131.2
4	CRC passed	-112	-18.2	-130.2
5	CRC passed	-110	-18.2	-128.2
6	CRC passed	-111	-18.5	-129.5
7	CRC passed	-112	-18.8	-130.8
8	CRC passed	-111	-19.2	-130.2
9	CRC passed	-112	-19.0	-131.0
10	CRC passed	-113	-18.8	-131.8

Table 10: Experimental results when using 151 dB attenuator (2450 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC failed	-	-	-
2	CRC failed	-	-	-
3	CRC failed	-	-	-
4	CRC failed	-	-	-
5	CRC failed	-	-	-
6	CRC failed	-	-	-
7	CRC failed	-	-	-
8	CRC failed	-	-	-
9	CRC failed	-	-	-
10	CRC failed	-	-	-

Table 11: Experimental results when using 152 dB attenuator (2750 km)

Test	CRC Result	RSSI (dBm)	SNR	Received power (dBm)
1	CRC failed	-	-	-
2	CRC failed	-	-	-
3	CRC failed	-	-	-
4	CRC failed	-	-	-
5	CRC failed	-	-	-
6	CRC failed	-	-	-
7	CRC failed	-	-	-
8	CRC failed	-	-	-
9	CRC failed	-	-	-
10	CRC failed	-	-	-

Table 12: Experimental results of all attenuated cases

Distance (km)	Attenuator (dB)	% success	AVG. RSSI (dBm)	AVG. SNR	Receive power (dBm)
500	137	100	-111.8	-5.87	-117.67
1000	143	100	-111.8	-13.35	--125.15
1500	146	100	-111.5	-17.49	-128.99
2000	149	100	-111.7	-17.48	-129.18
2200	150	100	-111.8	-18.71	-130.51
2450	151	0	-	-	-
2750	152	0	-	-	-

From the experimental results, we can verify that the end device and transmit data to gateway up to 2,200 km. However, the far field is still needed in order to confirm the capability of the transmission at the desired distance through the environment that might cause another loss on the path.

CONCLUSIONS

This paper overviews the THAIIOT 3U cubesat project that emphasis on the store and forward mission at about 600 km altitude. The selected technology for the long range and low power is the LoRa module and private LoRaWAN-server. The paper shows the design of both hardware and software coponents of the payload module. The calculated link budget showed that the LoRa technology can transmit and receive data at a distance up to 2000 km. By assuming the transmitted data size of 35 bytes, the possible maximum data rate was 292 bps, which required 1.81 s of Time on Air (ToA). Moreover, the experimental results verify the capability of the THAIIOT payload to successfully transmit the data up to 2,200 km.

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Appendix A

Item	Symbol	Units	Source	Parameter
Frequency	MHz	MHz	input	433.135
Range	km	km	input	2,000
Free space loss	FSL	dB	$L_{fs} = 32.4 + 20 * \log_{10} D + 20 * \log_{10} f$	151.198
Transmitter power	Ptx	dB	input	14.0
Transmission Antenna Gains	Gtx	dBi	input	5
Receive Antenna Gains	Grx	dBi	input	2
Losses from cable, connectors, branching unit Tx	Lchannel tx	dB	input	2
Losses from cable, connectors, branching unit Rx	Lchannel rx	dB	input	1
Receive Signal Level	RSL	dBm	$RSL = P_{tx}(dBm) + G_{tx}(dBi) + G_{rx}(dBi) - L_{channel\ tx}(dB) - L_{channel\ rx}(dB) - FSL$	-133.198
Bandwidth	BW	kHz	input	125
Noise Figure of Receiver	NF*	dB	input	2
Signal to Noise Ratio Limit	SNR	dB	input	-20
LoRa Sensitivity	S	dBm	$S = -174 + 10 \log_{10} BW + NF + SNR$	-141.031
Link budget	Link budget	dB	$Link\ budget = P_{TX}(dBm) - S(dBm)$	155.031
Fade margin	Margin	dB	Rx signal level (dB) – Rx sensitivity (dB)	**7.833**