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Development of a CubeSat Single Channel LoRa Receiver Module for Space-based IoT Application

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Abstract

CubeSat attracts many researchers due to its low production and deployment cost. One of the application is implemented in low data rate communication or machine to machine (M2M) with IoT devices in remote areas such as islands, forests, and mountains. In this study, a CubeSat receiver for IoT communication in remote areas has been developed and realized. A LoRa SX1276 chip is used for processing passband signals captured by the antenna. The device has a amplifier gain of 20.92 dB, 390 mW power consumption, and operating frequency of 923 MHz. The developed CubeSat is expected to provide a low bit rate of 5468.750 bps for SF 7 and 292.969 for SF 12, the receiver serves as a concentrator for monitoring devices in rural areas.

Keywords: CubeSat; ; LoRa; SX1276; M2M; IoT

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1. Introduction

In recent years, the development of satellite has advanced due to the emergence of CubeSat. This technology has helped pushed the research of outer space because it appeals to researchers due to its low design-and-deployment cost [1]. One of the many uses of a CubeSat is communicating with devices on earth, using this functionality a CubeSat can be used for monitoring, early-warning-system, or regular M2M (machine-to-machine) communication between the CubeSat and the monitoring device. Using this functionality, a CubeSat can communicate with a monitoring device that is placed in remote areas such as island, mountains, oceans, and many more.

CubeSat is a cube shaped satellite with different sizes and uses a standard measurement which 1U (U=unit) is equal to 10 cm^3 or 1-1.33 kg [2]. The CubeSat orbits in low earth orbit (LEO) between 400-1000 km. In general, a typical CubeSat consist of a communication system, command and data handling system, electrical power system, and altitude determination and control system [3].

Machine-to-machine (M2M) communication is a low data rate communication between devices using a network, the network can be wired or wireless, M2M can also communicate between multiple devices using a network like the Internet [4] or a LoRa network.

A LoRa module is a radio module that uses a type of spread spectrum modulation technique, that communicates in 900 MHz ISM bands. Due to the type of modulation and a low data rate this allows the module to communicate long ranges. A LoRa module can be used as a node, concentrator, or a gateway.

A research about the application of LoRa in CubeSat has been done by [5-7]. In the paper it is concluded that using a LoRa module is possible to reach a CubeSat in a LEO orbit. A CubeSat receiver using LoRa is not a new concept, there are already CubeSats deployed using this system such as Norby, VR3X-B-Petrie, and many more. One of the reasons to design a new receiver is that these CubeSat like Norby use the 433 MHz, 868 MHz, and 915 MHz

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frequencies, whereas in Indonesia the regulated frequency is in 920-923 MHz. In this paper a CubeSat receiver for 920-923 MHz has been developed using a LoRa module. It is different with [5-7], this paper focuses on developing a LoRa receiver for CubeSats instead of researching whether a LoRa module can be used for LEO satellites because from previous research have concluded that a LoRa module can reach the LEO orbit. This paper is hoped to help with communication of devices in rural areas and as a reference for the development of LoRa receivers for CubeSat in the future.

2. Research Methodology: Developing the CubeSat Receiver Module

There are already boards with a LoRa module and a microcontroller integrated in the same board such as the aurora board which integrates the ESP32 microcontroller with a LoRa module. The main reason for not using these boards is because these board doesn't include an RF amplifier in the board, another reason for not using the available board in the market is the form factor of the PCB that is used. For CubeSats a PC/104 form factor is sometimes used because it fits the standard size of the CubeSat and it can also be stacked therefore, saves space in the already small CubeSat.

2.1 Developing Process

Developing any boards takes time and need to be thought out. The process of developing the receiver is firstly, make a block diagram of the device as concept design. Secondly pick the main components that will be used to make the receiver. Then make the schematic of the receiver. After that, design the PCB and connect the components with traces. Lastly is to print the PCB and assemble it with components.

2.2 Block Diagram

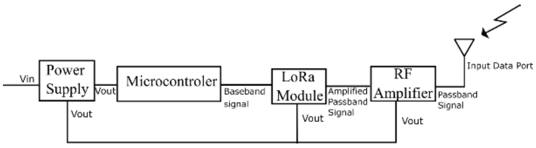

Fig. 1 Block Diagram of The Receiver Main Components.

The Fig. 1 depicts the relation of components to each other. As the RF signal is received by the antenna the amplifier amplifies the signal, then the amplified RF signal is then received by the LoRa module. The LoRa module converts the RF signal into a passband signal for the microcontroller to receive the data. The microcontroller controls the transmission configuration of the LoRa module and can also act as a temporary data storage. To power the components a regulated power supply is needed to not damage the components by having too much voltage.

2.3 Main Components

There are four main components that is used are microcontroller, LoRa module, power supply, and RF amplifier, the relation of the components can be seen in figure.

1. Microcontroller

The microcontroller in this application is only needed to write and read the registers of the LoRa module. Because the microcontroller's job is only to communicate with the LoRa module therefore, any microcontroller can be chosen but a powerful microcontroller is preferred for stability. The common microcontrollers are, ATmega328p, PIC16F877A, and STM32F103C8T6.

Table 1. Microcontroller Comparison.

MCU	Flash Memory	SRAM	Clock Speed	IO
STM32 F103C8T6	64 Kby.	20 Kby.	72 MHz	37
ATmega 328	32 Kby.	2 Kby.	20 MHz	28
PIC16F 877A	14 Kby.	368 Kby.	20 MHz	33

From Table 1 we can see that the STM32F103C8T6 chip is has the best specification than the rest of the chips. Another reason to choose this microcontroller is because it is relatively easy to incorporate with the need of minimal external components. The operating voltage of the chip is 3.3 V, but it can tolerate 2.6 – 3.6 V and it also has a CPU frequency of 72 MHz [8].

2. LoRa Module

In Indonesia, the regulated frequency for LoRa is between 920-923 MHz other than that it is forbidden. Therefore, the LoRa module that is allowed for the receiver is a SX1276, SX1277, or SX1279. The sensitivity of the SX1277 is not up to par with the rest of the chips hence it is better to choose between SX1276 and SX1279. Also, the availability of SX1276 module is better than the SX1279 thus the SX1276 module is chosen for the receiver.

Table 2. Lora Chip Comparisons [9].

Chip	Frequency Range	Sensitivity
SX1276	137-1020 MHz	-111 to -148 dBm
SX1277	137-1020 MHz	-111 to -139 dBm
SX1278	137-525 MHz	-111 to -148 dBm
SX1279	137-960 MHz	-111 to -148 dBm

3. Power Supply

The operating voltage of the LoRa module and the microcontroller chip is the same which is 3.3V. To power them with a stable voltage, a regulator is needed. AMS1117-3.3 is a suitable choice to perform this task because this regulator can supply up to 0.8-1.6 A [10].

4. RF Amplifier

To choose the RF amplifier, we must calculate the gain that is needed to accomplish outer space communication. To calculate the link budget the formula that is used is from [11] and the free space loss formula that is used is from ITU-R P.525-4. If we assume the orbit takes place at the altitude of 500 Km. The link budget that is achieved is shown at Table 3.

Table 3. Link Budget of The System Without RF amplifier.

Parameter	Value	Description
P_t	20 dBm	Transmitting power
G_r	2.5 dBi	Receiver antenna gain
L_t	0.05 dB	SMA connector insertion loss [12]
G_t	2.5 dBi	Transmitter antenna gain
L_r	0.05 dB	SMA connector insertion loss [12]
P_l	145.68 dB	Path loss when d= 500 km and f = 923 MHz
P_r		
P_r	-120.8 dBm	Minimal power that is received

The received power at the orbit 500 Km is -120.8 dBm, but the highest sensitivity of a SX1276 chip is -111 dBm. Therefore, an RF amplifier with a gain greater than 9.8 dB is needed. To summarize the RF amplifier specification that is needed are shown in Table 4.

Table 4. RF amplifier Specification That Is Need.

Parameter	Value
Gain	≥ 9.8
Operating voltage	3.3
Operating frequency	920-923

Using Table 4 we know which RF amplifier we need, here are the ICs that fit the criteria.

Table 5 Amplifier ICs Specifications [13].

ICs	Voltage (V)	Current (mA)	NF (dB)	Gain (dB)
ERA-3+	3-3.4	35	2.6	21
GALI-3+	3-4.1	35	3.5	21.1
MNA-4A+	2.8-5	70.6	4.4	15.1
MNA-5A+	2.8-5	31.8	3	21.9
MNA-6A+	2.8-5	92	2.7	22.3

Using the table above as reference, MNA-5A+ IC is picked as the RF amplifier because of the low current consumption with some trade-off in noise figure, also this IC is easier to design with compared to the ERA-3+ and GALI-3+ because it only requires some capacitors and resistors as the external components thus lowering production cost. If external components factors was not a factor, the best choice would be the ERA-3+ but unfortunately it requires an expensive RF choke as an external component.

2.4 Target Specification

Table 6. Target Specification of The Receiver.

Parameter	Value
Frequency	920-923 MHz
amplifier Gain	≥9.8 dB
Current limit	≤800 mA
Connected devices on a single channel	≥2

To have a device that can achieve outer space communication and efficient power consumption the device that is developed needs to fit target specification that is written in the Table 6 above.

2.5 PCB Design

To design the PCB the right trace width needs to be calculated first to facilitate the current. To calculate the trace width, we use the Eq (1) and (2) from IPC-D257 [14].

$$Area(mils^2) = \left(\frac{I[A]}{K \times T[^oC]^b}\right)^{\frac{1}{c}} \tag{1}$$

$$Width(mils) = \frac{\text{Area}[mils^2]}{\text{Thickness}[oz] \times 1.378\left[\frac{mils}{oz}\right]} \quad (2)$$

where, *I* is the maximum current needed, *T* is the constant temperature rise which is 10ºC, *b* is a constant of 0.44, *c* is a constant of 0.725, and *K* is a constant of 0.048. With the maximal current of the regulator of 0.8 mA therefor the minimal trace width needed is 0.22 mm.

A 50 Ω impedance microstrip trace is also needed to connect the RF part of the board, to determine the size of the trace Eq. (3) is used. The equation is from IPC-2221 [15] and it as follows:

$$Z_o = \frac{87}{\sqrt{\varepsilon_r + 1{,}41}} \, ln\left[\frac{5{,}98h}{0{,}8w + t}\right] \quad (3)$$

where, *εr* is the dielectric constant, *h* is the substrate height (inch), *w* is the trace width (inch), and *t* is the trace thickness (inch). From the manufacturer of the PCB we can know the dimension and dielectric constant of the PCB. For our PCB it has a 4.5 dielectric constant, 1 mm of substrate height, and 0.035 mm of trace thickness. Using the information we can find the trace width of the microstrip which is 1.8 mm.

2.6 Module Realization

After making the schematic and the PCB design. The next step is to print and solder the components. In Fig. 2 our receiver module that has been realized.

Fig. 2 The Receiver Module That is Realized.

Table 7 Dimensions and Mass of The Receiver Module.

Parameter	Value	Unit	Description
Length	93.7	mm	PCB Length x-axis
Width	89.6	mm	PCB Width y-axis
Thickness	1	mm	PCB width
Height	9.5	mm	PCB height at the header
Mass	31.4	gram	PCB mass with components and without antenna.

3. Testing and Measurement Result

3.1 Functionality Test

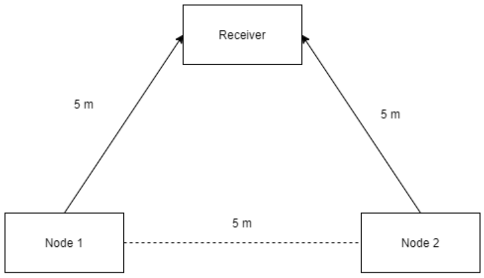

Fig. 3 The Scheme of The Test.

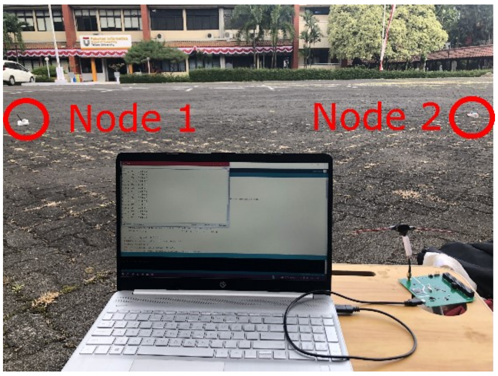

Fig. 4 Real Scheme of The Test.

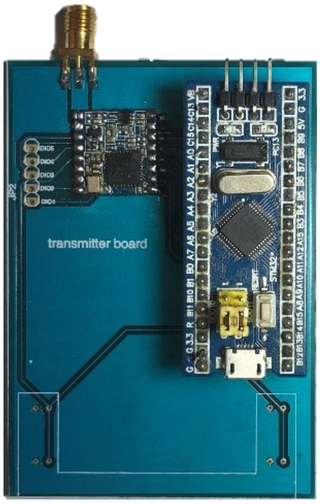

Fig. 5 Transmitter Node.

The scheme of this test is shown in Fig. 3 and Fig. 4 the nodes and the receiver is separated by 5 m, there will be ten messages that is sent by the nodes in Fig. *5* and the test will be repeated three times. There is two transmitter that is on the same frequency but has different time frames, also the bandwidth of the communication is 125 KHz using SF 12. The purpose of this test is too test whether the device can receive messages from two receiver and this test will determine if the target from Table 6 is reached.

Table 8. Receiving Logs from Two Nodes.

Node	Messages sent									
	1	2	3	4	5	6	7	8	9	10
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note: ✓ Successful X Unsuccessful

From Table 8 we can see that the device has successfully received all the messages from two transmitter, this means one of the target specifications from Table 6 has been met.

3.2 Power Consumption Measurement

There are three mode that you can configure in a LoRa module, the modes are sleep, idle, and receive. Each modes have different power consumption; the result of the measurement is shown in tables below.

Table 9. Test Result in Idle Mode.

Spec.	Min.	Typ.	Max.
Current	74.8 mA	75.5 mA	76.3 mA
Power	374 mW	377.5 mW	381.5 mW

Table 10. Test Result in Sleep Mode

Spec.	Min.	Typ.	Max.
Current	73 mA	74 mA	74.6 mA
Power	365 mW	370 mW	373 mW

Table 11. Test Result in Receive Mode.

Spec.	Min.	Typ.	Max.
Current	77.3 mA	78 mA	78.8 mA
Power	386.5 mW	390 mW	394 mW

The result of the measurement in Table 9, Table 10, and Table 11 shows that the receiving mode consumes 390 mW of power which is higher than idle and sleep mode. If the receiver does not expect any packets of data, to save more power idle or sleep mode can be switched from receiving mode.

The power consumption of this module is not efficient compared to the receiving board of Norby CubeSat, the Norby CubeSat receiving board has a power consumption of 175 mW [16] while the designed receiver module is 390 mW on receiving. To further improve the power consumption of the receiver perhaps it is better to use a buck converter rather than a voltage regulator and also a low power STM32 microcontroller.

3.3 RF Amplifier Gain Measurement

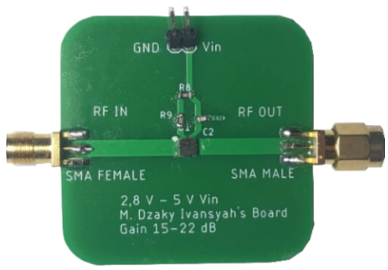

Fig. 6 RF amplifier Module.

To measure the gain of the amplifier a separate board needs to be created to measure the input and the output of the amplifier. Fig. 6 shows the RF amplifier that is used for the measurement. For the measuring instrument a spectrum analyzer is used, by using the tracking generation and the RF input port we can measure the gain of the RF amplifier. To power the RF amplifier a 3.3 V supply is used.

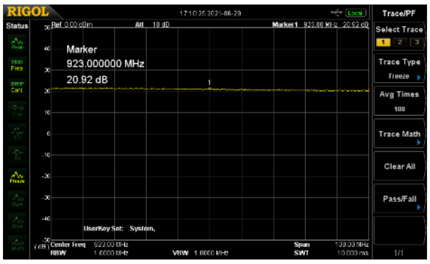

Fig. 7 Amplifier Gain Measurement At 923 MHz.

The reason to measure the gain of the RF amplifier is because we are interested of the gain of the RF amplifier using 3.3 V as the supply and 923 MHz frequency. The result in Fig. 7 shows the gain is 20.92 dB this value makes sense because the RF amplifier promises 15-22 dB of gain.

3.4 Operating Frequency of the Receiver

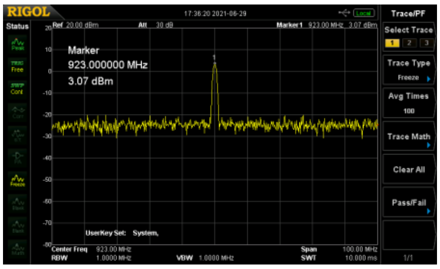

Fig. 8 Operating Frequency of The Transmitter.

The figure above shows the operating frequency of the transmitter. The reason of not measuring the receiver is because the receiver is incapable of transmitting packet because the RF amplifier is blocking the signal from the LoRa module. If we find the operating frequency of the transmitter that is used at the functionality test in section 3.1 we will also know the operating frequency of the receiver because the receiver has successfully received the packet from the receiver. In Fig. 8 the operating frequency of the transmitter is 923 MHz with a bandwidth of 125 KHz therefore the operating frequency of the receiver is also 923 MHz with 125 KHz bandwidth.

3.5 RSSI Measurement

The purpose of this measuring test is to find the best baud rate to apply in the receiver. The scheme of the test is LOS communication in an open field. The configuration of this test uses 125 KHz bandwidth and 17 dBm transmitting power. The relation between the baud rate and the spreading factor is shown in Eq (4) [17].

$$R_s = \frac{BW}{2^{SF}}\ symbol/second. \quad (4)$$

Table 12. RSSI Value measured with Various Spreading Factors and Distance.

SF	Baud rate	dist. (m)	RSSI (dBm) max	RSSI (dBm) Avg.	RSSI (dBm) min
7	976.5625	5	-13	-14.833	-18
		10	-14	-15.333	-19
		20	-23	-24.267	-27
10	122.0703125	5	-11	-12.5	-14
		10	-13	-14.433	-16
		20	-15	-16.967	-19
12	30.51757813	5	-3	-4.7333	-6
		10	-5	-6.0333	-7
		20	-12	-12.667	-15
		250	-71	-72.933	-75

Fig. 9 Location For the 250 m and SF 12 Long distance Test.

The result from Table 12 shows that the best configuration for outer space communication is to use the spreading factor 12, this is because it gives the lowest RSSI. The lower RSSI means adding more range to communication, but the communication needs to sacrifice speed of the baud rate to add more range. Also, the RSSI for at the distance of 250 m is -72.933 which is very low. As you can see in Fig. 9 the test is not ideal because trees and houses can cause multipath fading.

3.7 Bit Rate of CubeSat

The designed receiver is a single channel receiver therefore it cannot receive two or more data at once from different nodes. But if a multiple access algorithm like TDMA is applied it can communicate with tens or hundreds of IoT devices in a designated time frame, but the algorithm is not discussed in this paper.

The bit rate is important to know because it tells the maximum bit that can be received in each second. For determining the nominal bit rate of the device Eq (5) can be used [17].

$$R_b = SF \times rate\ code\ \times\ R_s \quad (5)$$

where, rate code is a fraction of 4/5, 4/6, 4/7, or 4/8. Using a rate code of 4/5 and 125 KHz bandwidth the achieved bit rate is shown in Table 13.

Table 13 The Achieved Bit Rate.

SF	Bit Rate (bit/sec)
7	5468.750
10	976.563
12	292.969

3.7 Link Budget Assuming CubeSat is in Orbit

The purpose of this test is to analyze whether the receiver can communicate with end nodes on Earth.

Table 14. Link Budget of The Assumed CubeSat with the RF amplifier Attached

Parameter	Value	Description
P_t	20 dBm	Transmitting power
G_r	2.5 dBi	Receiver antenna gain
L_t	0.05 dB	SMA connector insertion loss [12]
G_t	2.5 dBi	Transmitter antenna gain
L_r	0.05 dB	SMA connector insertion loss [12]
G_{Amp}	20.92 dB	amplifier Gain
P_l	145.68 dB	Path loss when d= 500 km and f = 923 MHz
P_r		
P_r	−99.86 dBm	Minimal power that is received

The assumed power received is -99.86 dBm, with the highest LoRa sensitivity being -111 dBm. It can be concluded that communication between the CubeSat in outer space and the end nodes on Earth is successful.

4. Conclusion

This paper has successfully made a LoRa based CubeSat receiver by using a SX1276 module, MNA-5A+ IC, STM32 MCU, and a 3.3V power supply. The receiver that has been developed fit all the target specification that has been set in Table 6. The developed receiver has a RF amplifier gain of 20.92 dB, operating frequency of 923 MHz, power consumption of 390 mW in receiving mode, and PC/104 form factor. For future endeavors a multi-channel receiver can be made by using a SX1301 module and a Raspberry Pi.

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