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Design of an adaptive CubeSat transmitter for achieving optimum signal-to-noise ratio (SNR)

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Abstract. CubeSat technology has opened the opportunity to conduct space-related researches at a relatively low cost. Typical approach to maintain an affordable cubeSat mission is to use a simple communication system, which is based on UHF link with fixed-transmit power and data rate. However, CubeSat in the Low Earth Orbit (LEO) does not have relative motion with the earth rotation, resulting in variable propagation path length that affects the transmission signal. A transmitter with adaptive capability to select multiple sets of data rate and radio frequency (RF) transmit power is proposed to improve and optimise the link. This paper presents the adaptive UHF transmitter design as a solution to overcome the variability of the propagation path. The transmitter output power is adjustable from 0.5W to 2W according to the mode of operations and satellite power limitations. The transmitter is designed to have four selectable modes to achieve the optimum signal-to-noise ratio (SNR) and efficient power consumption based on the link budget analysis and satellite requirement. Three prototypes are developed and tested for space-environment conditions such as the radiation test. The Total Ionizing Dose measurements are conducted in the radiation test done at Malaysia Nuclear Agency Laboratory. The results from this test have proven that the adaptive transmitter can perform its operation with estimated more than seven months in orbit. This radiation test using gamma source with 1.5krad exposure is the first one conducted for a satellite program in Malaysia.

1. Introduction

The cubeSat platform has been used in space-related researches as technology demonstration. It is a relatively low cost option as compared to other space technology platforms like geostationary satellite that requires development cost up to more than USD300 million for the smallest single-satellite and several billion dollars for a multi-satellite global system [1]. The typical cubeSat employs a simple communication system using ultra high frequency (UHF) band with fixed transmit power and data rate to maintain the development cost at an affordable price [2]. However, a satellite that is orbiting the low earth orbit (LEO) does not have relative motion with the earth rotation. This LEO condition will create variability of distance for the transmission signal from the satellite to the ground station. The satellite communication field of view will be available when it is passing the ground station at above of 0° seen by the ground station's antenna elevation angle, which ranges from 5° to 90°. The satellite distance will be maximum when the antenna elevation angle is minimum. For a simple communication system, the transmission power is fixed at the minimum power that could ensure the link margin is available at the most extended satellite distance, which is at the minimum value of the ground station's antenna elevation

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angle [3]. A transmitter with adaptive capability is proposed to adapt to the variable receiving antenna elevation angle hence, improving and optimising the satellite link.

For a typical satellite mission, the link budget is analysed at the worst channel condition and at the minimum receiving antenna elevation angle to achieve the link margin. The satellite transmitter will have a fixed radio frequency (RF) transmit power and data transmission rate. The RF transmit power is set to fixed amount that could make a transmission for the longest satellite distance available, which means the Free Space Loss (FSL) is at maximum value. The satellite transmitter will maintain the RF transmit power even though at lower FSL. Based on conducted studies, RazakSAT satellite in LEO is consistently transmitting signal at antenna elevation angle that varies from 10° to 23° [4]. The received power signals are varied and not at the optimum signal-to-noise ratio (SNR).

CubeSat data rate is selected based on the amount of collected data in the mission and the average of satellite contact time. An effective data rate will depend on the SNR, which is composed of other factors such as the RF transmit power and the antenna elevation angle, which will also determine the satellite contact time. The satellite payload capabilities will be limited and scientific duty cycle will be reduced by using maximum downlink rate [5]. Satellite data rate is primarily limited by the available link power budget rather than the available radio electronics technology [6]. This finding shows that even though the maximum data rate would allow more data to be transmitted to the ground station, the link power budget will limit the cumulative data collected. A trade-off study of the transmission data budget with satellite contact duration using the satellite simulation toolkit for downloading needs to be performed. Using a transmitter with multi-mode operation, the SNR will be at the optimum level since the adaptive function will be determined by the ground station's antenna elevation angle.

There are several CubeSats carrying a payload that uses Software Defined Radio (SDR) solutions [7]. SDR is implemented due to its flexibility that allows it to be configured. For example, SDR allows receiver frequency in the payload to be tunable as demonstrated in GOMX1 developed by Gomspace [8]. Other than SDR, System On Chip (SOC) solution is also capable of providing adaptive function for transceivers. This solution is widely used in the mobile computing technology due to its highly integrated circuit and low power consumption compared to SDR [9]. In this project, the Automated Gain Control (AGC) amplifier is using the SOC solution that allows the RF transmit power and data rate to be reconfigured.

This paper presents the adaptive UHF transmitter as a solution to overcome the variability of path loss in the propagation path. The transmitter is designed to have four selectable modes of operation with different data rates and RF transmission power to achieve optimum SNR and efficient power consumption. The adaptive capability will influence the amount of data downlink to suit the satellite operation. The transmitter is developed with the capability to be integrated with other CubeSat bus sub-systems. The prototype is designed and tested to be compatible with the interface of the other sub-systems such as power modules, On Board Computer (OBC), antenna, satellite structure, electrical grounding and satellite thermal condition.

2. Methodology

The primary target of this research is to develop a CubeSat transmitter with adaptive capability. The link budget and data trade-off analyses are performed to set the transmitter multi-mode specification. The RF simulation using the Advance Device System (ADS) software is conducted to an optimised transmitter design. The circuitry and printed circuit board (PCB) designs are developed using Protel DXP. The PCB is then fabricated using an in-house manufacturing process.

2.1 Link Budget and Data Transmission Analysis

The transmitter is developed as one of the subsystems in the TiGA-U CubeSat mission [10]. In the satellite mission study, the satellite altitude is 700 km and the ground station antenna's elevation angle varies from 0° to 90°. The satellite is using an omni-directional antenna with a gain of 0dBi while the ground station uses directional tracking Yagi antenna with 15.9 dBi gain. The RF transmit power from 0.5W to 2W, with an increment of 0.5W for each step, is used in the link budget analysis. Additional

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input that represents the adaptive RF transmit power is also included in the analysis to show that the optimum SNR is achievable. Satellite Concepts of Operation (CONOPS) and data transmission trade-off are used to generate the adaptive multi-mode specification. From the analysis, the input and output configuration of the adaptive controller is created.

2.2 RF System Design Simulation

The design process is started using the standard fixed transmitter architecture before using frequency synthesiser with the AGC. Then, the transmitter is set using a cascade gain analysis to determine the gain required at each stage of the system until it reaches the required transmitter output power. Using ADS software, system level design simulation has been performed to achieve the preliminary system specification. Figure 1 shows the Gain Budget Analysis simulation setup for the three stages of the amplifier: AGC amplifier, preamp and High Power Amplifier (HPA) at 2W of RF transmit power. The simulations are also repeated for 0.5W and 1W of RF transmit power.

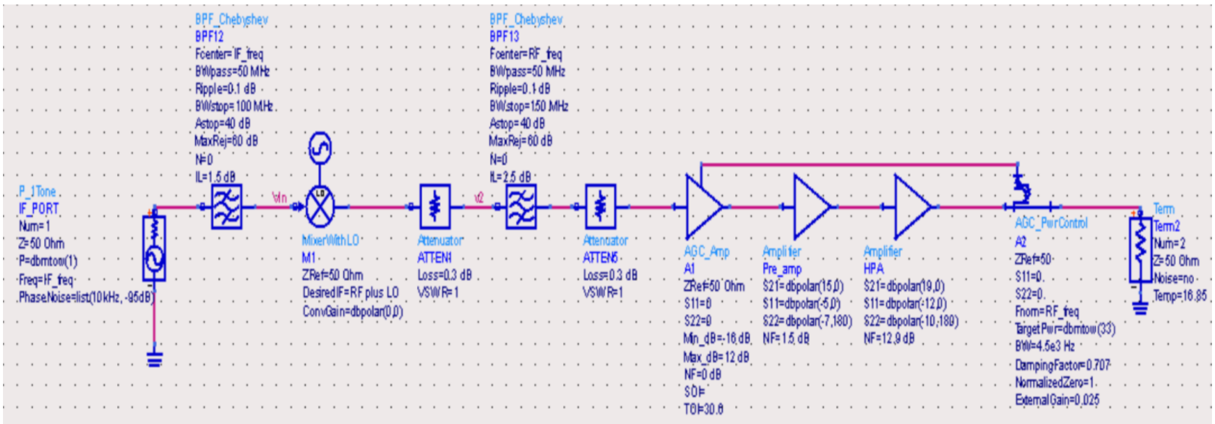

Figure 1: Transmitter system level design

From the system level analysis and circuit design simulation results, the transmitter specification is produced as tabulated in Table 1. The physical size of the transmitter is using the standard size of CubeSat module with PCB connector location that allows for stacking with other CubeSat subsystem modules. The transmitter is designed with an interface to the other subsystems such as antenna, power module and OBC as shown in Figure 2. The adaptive capability only involves the synthesiser module where the data rate and gain of the AGC amplifier can be configured. Other modules such as pre-amp and HPA are designed with a fixed configuration.

Table 1: UHF transmitter specification

Item	**Specification**
Frequency	430 - 440 MHz (UHF band)
Transmit Output Power	0.5 to 2 W
Data Rate	9.6kbps, 19.2kbps
Phase Noise at 10kHz Offset	<-95 dBc/Hz
Interface	UART, SMA connector
Power Supply	3.3V, 5V
Current (max)	0.6 A
Power Consumption	<5W
Dimension	91mm x 96mm x 15mm

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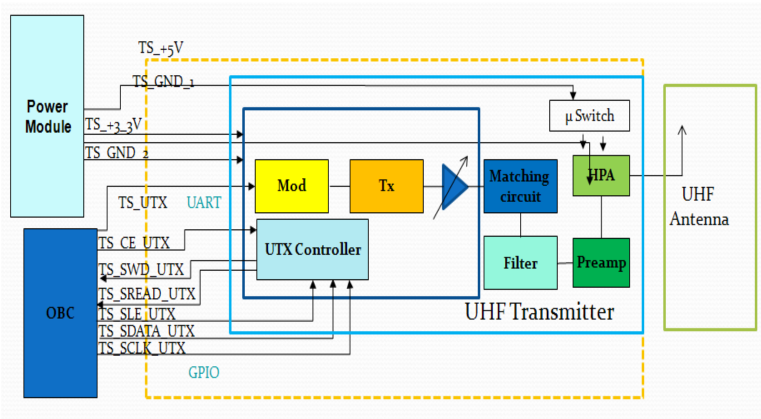

Figure 2: Block Diagram of UHF Transmitter

2.3 Prototype Development and Functional Test

From system level simulation, ideal components specification is replaced with available components in the market and the transmitter design is then optimized. The parts are then purchased and tested separately. The PCB design is fabricated using Computer Numerical Control (CNC) milling machine with two-layer copper PCB. The major sections of the upper layer are the voltage source with most of signals track. The bottom layer consists of ground signals and interconnected signals. Three prototypes are developed for the adaptive transmitter and each module is tested for functionality. The functional test measurements are performed in the lab environment to benchmark the specifications by using a spectrum analyser with counter, power measurement and phase noise measurement functions.

2.4 Space Environmental-Radiation Test

For the radiation test reference, the MicroMAS system expected mission dose is used. The CubeSat is designed for a one-year mission in LEO with a nominal orbit of 402 x 424 km and 51.6° inclination. Based on estimates from SPENVIS tool [11], a one-year mission dose is approximately 1.2 krad(Si). The Total Ionizing Dose (TID) test is conducted at the Malaysia Nuclear Agency- Gamma laboratory in Kajang, Selangor as shown in Figure 3. The high dose rate gamma source, Cobalt 60 is used in this TID test. The transmitter is exposed to the gamma source in 15-minute intervals and each exposure is at 100rad. The total exposure duration is 233 minutes and the estimated TID is 1553rad.

Figure 3: Radiation test setup at Malaysia Nuclear Agency

3. Results and Discussion

In this section, each of the methods implemented during development of the transmitter is discussed. Results that are collected from the link budget analysis until the environment test are described.

3.1 Link Budget and Data Transmission Analysis

Based on the link budget analysis, the SNR outputs at the receiving antenna are plotted for various elevation angles that range from 5° until 90°. The plot is combined with the RF transmission power that is fixed at 0.5W, 1W, 1.5W and 2W as shown in Figure 4. The minimum threshold to establish a transmission link between satellite and ground station is set at the required SNR based on the data rate with additional 3dB margin at the preliminary satellite design stage [12]. The SNR outputs for the adaptive RF transmit power are also plotted to highlight that, with the capability of choosing the RF transmit power, SNR outputs are optimised compared to the transmitter with fixed RF output power. From the link budget analysis, data rate trade of between 9,600bps, 19,200 bps, and 38,400 bps are recorded, and the relationship between data rate, minimum receiving antenna elevation angle and RF transmit power are tabulated in Table 2.

The satellite in LEO typically provides 10-15 minutes of visibility from the ground station. The receiving antenna elevation angle during the passing of the satellite as viewed by the ground station can be predicted and computed using a simulation program [13]. By knowing the elevation angle in advance, the transmitter can adapt to the required RF transmit power and the data rate for optimum SNR. The satellite contact duration simulation is performed using Software Toolbox Kit software. The maximum data transmission during satellite contact duration simulated by STK is calculated and listed in Table 2.

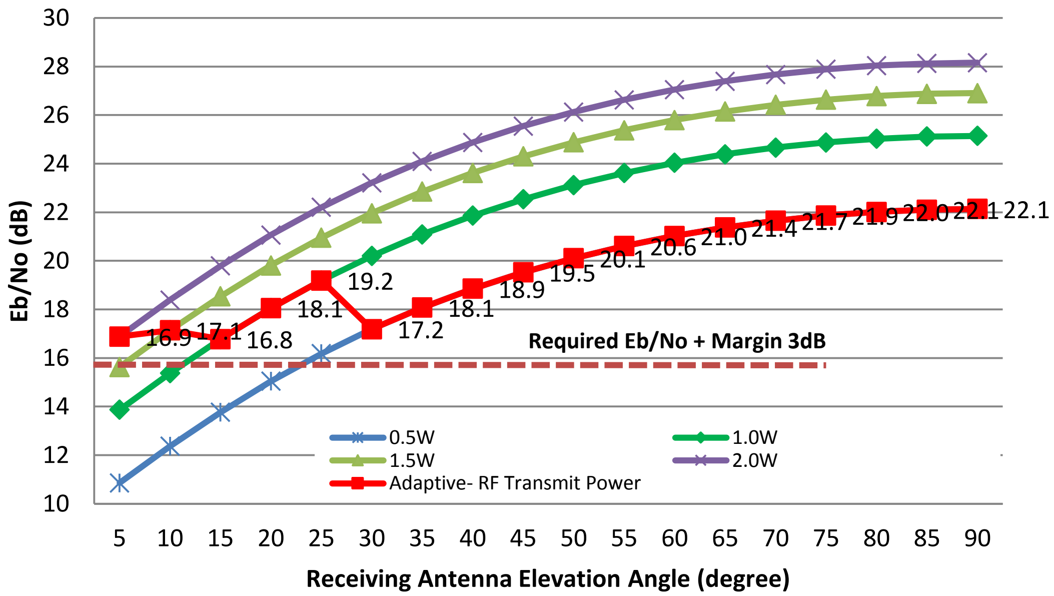

Figure 4: Link budget analysis results for 19,200bps data rate

Table 2: Relationship between data rate, minimum receiving antenna elevation angle and RF transmit power

Transmission data rate (bps)	Maximum data transmit during satellite contact duration (kilobyte)	Minimum Receiving antenna elevation angle (°)	RF Transmit power (W)
9600	469	10	0.5
9600	594	5	1
19200	933	15	1
19200	1,426	5	2
38400	3,027	25	2

From Table 2, the inputs that will determine the selection of RF transmit power and data rate are simplified as shown in Table 3. The receive antenna elevation angle predictions for each satellite path are available in OBC based on input from the Attitude Determination and Control (ADCS) subsystem. The input from power module or battery condition is also available in the OBC or direct input from the power module. The nominal power condition means that the satellite is in optimum condition and is capable of performing any satellite operation. The safe mode is determined as the satellite is in low power. Therefore, only housekeeping data can be sent to the ground station. Data transmission input is available from OBC based on the satellite operational condition (i.e. whether it is on Payload Data Downloading or only housekeeping data).

Table 3: Input and output configuration for multi-mode operation

Input Selection			**Controller Output**	
Minimum Receiving Antenna Elevation Angle (°)	**Power Module / Battery Condition**	**Data Transmission**	**RF Transmit Power (W)**	**Data Rate (bps)**
5	Nominal	Big Data	2	19,200
15	Nominal	Big Data	1	19,200
5	Nominal	Nominal	1	9,600
10	Safe Mode / Eclipse	Nominal	0.5	9,600

3.2 Simulation Results

From system level until the circuit and PCB layout design, RF parameters such as RF transmit power, phase noise, spurious and amplifier gain are monitored. These parameters are optimised before the actual circuit is designed. Figure 5 and Figure 6 show the simulation results, which are summarized in Table 4.

Meas_Name	A1	HPA	Pre_amp	A2
Cmp_S21_dB	4.419	19.000	15.000	0.000
NF_RefIn_dB	2.500	3.995	3.104	3.995
OutPGain_dB	0.256	33.927	15.589	33.927
OutPwr_dBm	-0.744	32.927	14.589	32.927
OutNPwrTotal_dBm	-171.210	-134.987	-155.162	-134.987
OutTOI_dBm	30.600	46.151	36.273	45.771

Figure 5: Cascade gain budget simulation results

freq	Mix(1)	Mix(2)	Spur_dBc	spec_dBm
0.0000 Hz	0	0	-184.981	-151.768
70.00 MHz	1	0	-152.732	-119.520
140.0 MHz	2	0	-156.093	-122.880
150.0 MHz	-3	1	-190.836	-157.624
210.0 MHz	3	0	-230.264	-197.051
220.0 MHz	-2	1	-243.071	-209.859
290.0 MHz	-1	1	-163.196	-129.984
360.0 MHz	0	1	-141.229	-108.016
430.0 MHz	1	1	0.000	33.213
500.0 MHz	2	1	-137.762	-104.549
570.0 MHz	3	1	-162.553	-129.340
580.0 MHz	-2	2	-182.797	-149.585
650.0 MHz	-1	2	-235.977	-202.764
720.0 MHz	0	2	-155.320	-122.108
790.0 MHz	1	2	-153.472	-120.259
860.0 MHz	2	2	-180.885	-147.672

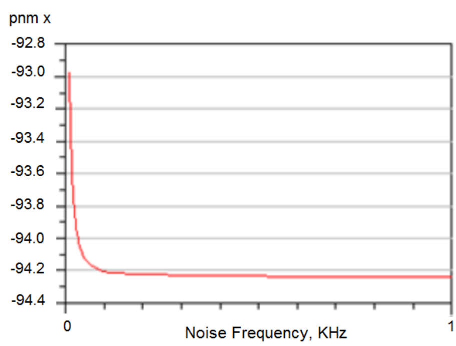

Figure 6: Spurious and phase noise simulation results

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Table 4: Transmitter simulation results

Item	Specification
Frequency	430 - 440 MHz (UHF band)
Transmit Output Power	0.5 to 2 W
Data Rate	9.6kbps, 19.2kbps
Phase Noise at 10kHz Offset	-95 dBc/Hz
Spurious	-137 dBc

3.3 Prototype Development and Functional Test Results

The PCB is designed for two-layer PCB layout, which is limited by the capability of the prototyping milling machine available in-house. The PCB casing is also designed and fabricated to support thermal conductivity for HPA for long hours of transmission. Figure 7 shows the PCB layout with mechanical chasing design. After completing the PCB fabrication, electronics components are soldered and tested for their functionality. Figure 7 also depicts the Qualification Model (QM), which is produced as the third prototype. The functional test results are summarized in Table 5.

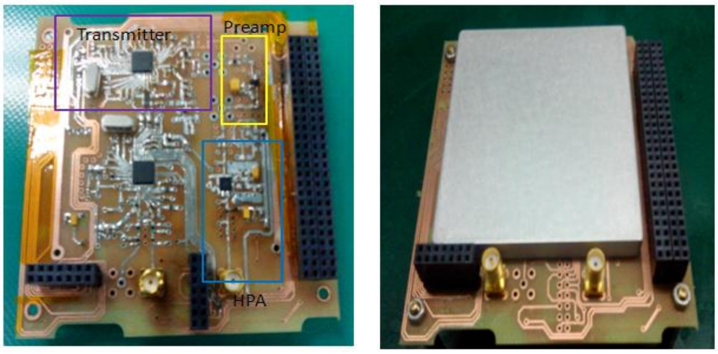

Figure 7: Qualification model (QM)

Table 5: Functional test results

Test Item	Requirement	Performance	Compliance
Frequency	437.325 MHz (UHF band)	437.325 MHz (UHF band)	Fully Comply
Transmit Output Power	0.5 to 2 W (27 to 33 dBm)	27.0 dBm 30.0 dBm 31.5 dBm 33.0 dBm	Fully Comply
Phase Noise at 10kHz offset	<-85 dBc/Hz	-95 dBc/Hz	Fully Comply

3.4 TID Test Results

The transmitter is turned ON before and after the chamber is closed to make sure that everything is in excellent condition before the gamma exposure is started. It takes about four hours to complete the 1.5krads of total gamma exposure. The transmitter is also turn ON and OFF when chamber is closed. The recorded RF power reading is +7.5dBm before deducting the losses and attenuation, with an equivalent value of 23dB. Therefore, the result is +30 dBm. This result is taken when the adaptive power control function is configured at 1W or +30dBm. The transmitter is fully functioning before and after the TID test. The ON and OFF of RF transmit power has been configured during the exposure of gamma source and does not appear to have any difficulty to transmit at the expected RF output power. The transmitter is also turned ON and reconfigured at the desired downlink frequency and manage to oscillate to the required result as shown in Table 6.

Table 6: Radiation test results

Item	**Specification**	**Before Radiation Test (0 krad)**	**After Radiation Test (1.53 krad)**	**Verification**	**Compliance**
Visual Inspection	-	Components and soldering pad in good condition.	Components and soldering pad in good condition.	Inspection	Fully Comply
Downlink Frequency	UHF-band, ~437.325 MHz	UHF-band, ~437.325 MHz	UHF-band, ~437.325 MHz	Test	Fully Comply
Downlink RF Transmit Power	30 dBm ± 0.5	30.1 dBm	30.1 dBm	Test	Fully Comply
Current Reading at 3V @ Transmitter SOC	26 mA	26mA	26mA	Test	Fully Comply

4. Conclusion

The UHF transmitter with adaptive multi-mode function is designed and developed in this research. This paper focuses on the design, validation methodology in the space radiation condition and the analysis of the adaptive multi-mode function. The connection between the RF transmit power, receive antenna elevation angle and data rate is investigated through the link budget analysis and CONOPS consideration. From the results, the adaptive multi-mode operation for the transmitter is designed with the capability to reconfigure the data rate and RF transmit power. The proof of concept, EM and QM models have been developed and validated. The transmitter uses industrial grade components that are fully in compliance with the RF output power and frequency stability requirement in a wide operating temperature range for the space environment. The multi-mode control function has also been tested and demonstrated to be functioning in the radiation test. The results show potential improvement in the CubeSat performance with regards to SNR and power consumption by adopting multi-mode control function.

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