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# Design and validation of an adaptive CubeSat transmitter system

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ABSTRACT

CubeSat in low earth orbit (LEO) primarily uses an amateur radio-band transmitter with a fixed specification. Nevertheless, the LEO satellite does not have an orbital velocity that equates to one sidereal day. Therefore, the ground station antenna views the satellite at different elevation angles which result in varied propagation path lengths. In this paper, an adaptive transmitter is designed to optimise the LEO satellite communication link and overcome the variability of the propagation path length issue due to different ground station elevation angles. A satellite communication link and operation analyses are performed to identify the relationship between the variation of the elevation angle so as to determine the optimum signal-to-noise ratio (SNR), improve data rate and increase the power efficiency of an adaptive link. Based on the results, a model is developed to control the adaptive configuration. The SNR and power consumption performance of the developed transmitter is compared with commercial transmitters. The results indicate that the transmitter output power is adjustable from 0.5 W to 1 W, and the data rate is selectable between 9600 bps and 19,200 bps. Compared to other CubeSat transmitters, the developed adaptive transmitter demonstrates more than 20% improvement in terms of SNR optimisation, additional throughput and power reduction.

## 1. Introduction

The use of the CubeSat standard sharply reduces the cost of developing and launching a satellite [1]. CubeSats are the best lower-cost alternatives for scientific experimental, educational and commercial space missions, where the satellite bus platform is cheaper compared to the overall satellite program [2]. CubeSat is a nanosatellite with a mass less than 4.5 kg and has limited operational power, in the range of 10–15 W [3]. There are three major subsystems in the CubeSat bus: the electrical power subsystem, radio frequency (RF) subsystem and onboard computer (OBC) [4]. The RF subsystem function is to transmit the payload data and the telemetry of the satellite bus. To design an RF communication subsystem, a link budget is calculated using the orbital parameters of the satellite mission to ensure an adequate link margin. CubeSat typically uses LEO due to a power limitation; it travels at much higher angular speeds to remain in orbit since it requires greater centrifugal force to balance the high gravitational force. Unlike the communication satellites in a geostationary orbit, CubeSat in LEO does not have relative motion with the Earth's rotation, resulting in a variable of propagation paths or proportional changes of free space path loss at each satellite contact time [5,6].

The standard practice in designing the satellite transmitter is to ensure that there is an acceptable link margin at the maximum propagation path between the satellite and ground station [7]. In order for a CubeSat to maintain a simple communication system, a fixed transmitter is designed to consistently transmit at the maximum capability, even at shorter propagation path [8]. Numerous studies have been conducted to prove that the variation of satellite distance due to the elevation angle could be improved by link adaptive methods. An adaptive modulation algorithm for downlink Multi-Carrier Code Division Multiple Access (MC-CDMA) systems is an example of a link adaptation method; developed by Kuo & Lu [9]. This research proves that the adaptation link method can achieve higher throughput, guaranteeing the required bit-error-rate (BER) and reducing the blocking probability. Based on a similar concept, a link adaptation algorithm for an adaptive time division multiple access (TDMA) also demonstrated to increase data throughput for wideband networking waveform in [10]. Research on designing an adaptive CubeSat communication sub-system and how the adaptive method influenced the LEO operational constraint had been published in [11]. Based on these link adaptation studies, an adaptive transmitter system proved to enhance transmission efficiency and satellite performance.

In terms of implementation, an adaptive transmitter requires a flexible platform to execute the link adaptation algorithm. Due to the demand for flexible implementation, software-defined radio

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(SDR) was introduced to develop an adaptive communication subsystem for CubeSat [12,13]. For example, GOMX1 CubeSat was developed by GomSpace [14] and uses SDR implementation to tune the receiver frequency. Aerospace Corporation is a satellite manufacturer which has developed an adaptive transmitter that is also capable of reconfiguring modulation techniques and optimising SNR performance [15]. Other than SDR, the System-On-Chip (SOC) solution is also efficient in implementing an adaptive function for the transceiver. The Surrey Research Centre [13] has improved their satellite performance by developing an SDR architecture in Field Programmable Gate Array (FPGA) and paired it with an RF programmable transceiver SOC to solve back-end and front-end re-configurable challenges.

The elevation angle of a satellite pass must be predicted in advance as part of adaptive algorithm implementation, and the computation can be conducted using a simulation program [16]. Nowadays, a commercial satellite orbit simulation and prediction program simplify the complicated task of calculating orbit dynamics. In the RazakSat operation, the orbit propagator software produces the parameters required for each pass such as the elevation angle, transmitter turn-on time and duration during each satellite pass [17]. The same approach can be used by CubeSat to generate the required input for the adaptive transmitter. By knowing the elevation angle beforehand, a transmitter with the capability of adjusting the RF transmit power and data rate can optimise the power consumption and SNR. The adaptive transmitter with SOC implementation allows the RF transmit power and the data rate to be reconfigured, reducing the propagation path variation problem.

The rest of the paper is organised as follows. Section 2 discusses the methodology of an adaptive transmitter hardware design and the Adaptive Transmitter Control Unit (ATCU) model configuration. Section 3 presents the results and discussion of the developed transmitter, as well as a comparison with commercial transmitters. Finally, Section 4 provides the conclusion and future work.

## 2. Methodology

### 2.1. Transmitter design and hardware development

The UHF transmission system guarantees the transmission of telemetry and image data from the satellite to the ground station. It consists of a baseband modulator module and a transmitter module. The baseband modulator works at 9.6 kbps or 19.2 kbps data rate using Gaussian Frequency Shift Keying (GFSK) modulation technique. The frequency range for the transmission carrier is from 430 MHz to 440 MHz. The transmitter specifications are listed in Table 1.

The developed adaptive transmitter is shown in Fig. 1. The transmitter is designed with an interface to other subsystems such as the antenna, Power Module and OBC; as displayed in Fig. 2. The adaptive function only involves the synthesiser module where the data rate and gain of the automatic gain control (AGC) amplifier can be configured. Other modules such as pre-amp and high-power amplifier (HPA) are designed with a fixed configuration.

**Table 1**
Transmitter Hardware Specifications.

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

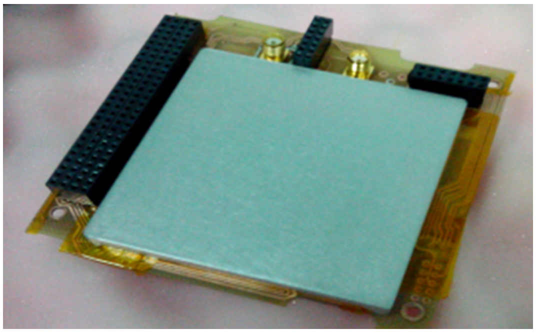

**Fig. 1.** The developed adaptive transmitter.

The transmitter consists of Transmitter-System On-Chip (TSOC), preamp or driver amplifier and HPA. The main transmitter module, such as the modulator and frequency synthesisers, are in the TSOC module. From Fig. 2, the modulator module is represented as Mod and the frequency synthesiser module is represented as Tx. The frequency synthesiser is targeted to achieve phase noise performance of less than −100 dBc/Hz at 10 kHz offset. The TSOC output power is programmable in 63 steps, from −16 dBm to +13 dBm, and has an automatic power ramp control to prevent spectral splatter. Programmable step size is 0.46 dB. The preamp and HPA increase the RF transmit output power to +33 dBm.

There are three amplifiers in the transmitter, and each amplifier is required to produce the minimum gain. The main parameters that must be validated are the gain, RF output power and power consumption. In Table 2, each gain of the amplifiers is listed; only AGC which is part of the TSOC module has the capability to reconfigure its gain. The AGC amplifier gain value is configurable in orbit, while the gain for both the driver amplifier and HPA are optimised and fixed at the transmit frequency before the satellite is launched. For the RF to transmit the output of 1 W or +30 dBm, the AGC should be configured to 4 dBm, as shown in Table 2.

At an early stage of the research work, the adaptive transmitter was designed to have 4 different outputs [18]. Based on a survey conducted by Klofas [8], the typical RF transmit power used by CubeSats are 0.5 W, 1 W and 2 W. Other power levels may be considered for future development to improve SNR, but this will simultaneously increase the test duration and cost; especially space environmental test cost. The selected components have the capability to increase the output power from 0.5 W to 2 W. The AGC digital setup for a diverse set of outputs is calculated using Table 2. Even though the hardware design has the ability to increase power by up to 2 W, only 0.5 W and 1 W were selected for the ATCU model. The power selections are based on the new model design in this paper which do not require 2 W transmit power.

### 2.2. ATCU model design

In a CubeSat design, one of the major factors to consider is the CubeSat dimension. The CubeSat dimension limits the capability of solar panel power generation with less than 6 W for 3U body mounted solar panel [12,19]. These power levels are incompatible with high energy payloads such as imaging radars, and lidars. For CubeSat bus, these constraints also limit the power, especially for the communication subsystem. The communication subsystem consists of a transmitter and receiver, but only the transmitter has a direct impact on the satellite system design since it requires

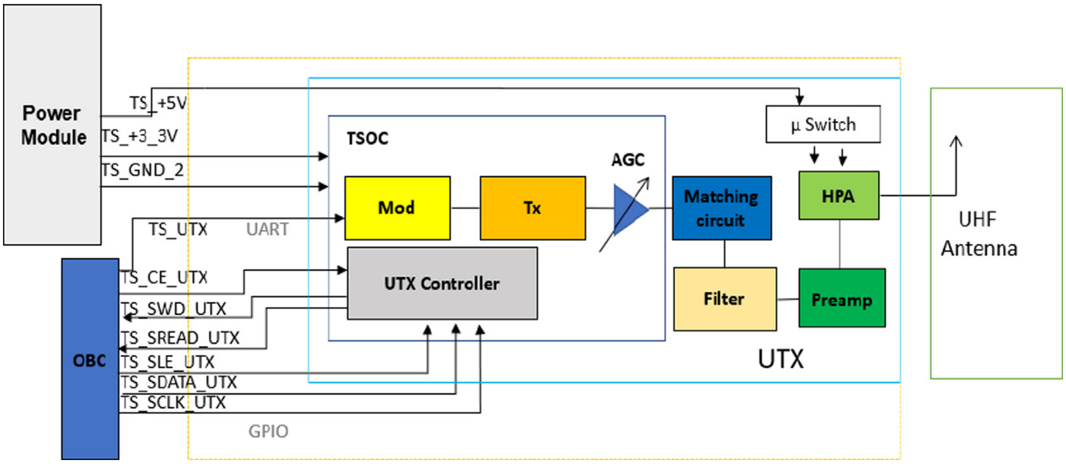

**Fig. 2.** Block diagram of the UHF transmitter.

**Table 2**
RF Transmit Power Budget.

| Item | Tx with AGC | Driver Amplifier | HPA | Coax & antenna Feed | Antenna |
|---|---|---|---|---|---|
| Gain (dB) | | 14 | 12 | −0.2 | 0 |
| Output Power (W) | | 0.1 | 1.0 | 1.0 | 1.0 |
| Output Power (dBm) | 4 | 18 | 30 | 29.8 | 29.8 |
| P1 dB (dBm) | 13 | 22 | 32.5 | | |

power to transmit payload data. The transmitter requires the most power due to the RF amplifiers and the high duty cycle of periodic beacon transmission to establishing contact with the ground station at satellite pass [7,20]. The link budget equation for a digital satellite communication link is shown below:

$$\frac{E_b}{N_o} = \frac{P_t L_l G_t L_s L_a G_r}{k T_S R} \tag{1}$$

where $E_b/N_o$ is the ratio of received energy-per-bit to noise-density, $P_t$ is the transmitter power, $L_l$ is the transmitter-to-antenna line loss, $G_t$ is the transmit antenna gain, $L_s$ is space loss, $L_a$ is transmission path loss, $G_r$ is the receive antenna gain, $k$ is the Boltzmann's constant, $T_s$ is the system noise temperature and $R$ is the data rate. When an orbit is selected and the distance between the satellite transmitter to the ground station receiver are determined, the primary link variables which affect system cost are$P_t$, $G_t$, $G_r$, and R [5]. In this research, the satellite antenna and the receiving antenna are considered constant value by adopting existing available subsystem design for TiGA-U CubeSat. The transmit power and data rate are the remaining factors that could be optimised.

Most nano-satellites or CubeSats have multiple data rates to meet satellite mission requirements but do not have multiple RF transmitting power [17]. This condition reduces the satellite contact time but allows for higher data rate during transmission [15]. Therefore, by using the adaptive transmitter in the CubeSat mission, a combination of high and low data rate is configured to produce a higher data throughput transmission with longer contact time. The transmitter hardware is designed to have the capability of reconfiguring the data rate and the RF transmit power. By adopting this technique, the transmission link SNR is expected more optimise, data throughput will be increased and the power consumption is reduced. For digital modulation with the noise bandwidth and the signal bandwidth or the symbol rate, are the same, then $E_b/N_o$ is equivalences to SNR [21]. In order to evaluate the transmitter performance in terms of SNR condition [22], the root-mean-square error (RMSE) of SNR data are calculated using the following equation

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\dot{y}_i - y_i)^2}{n}} \tag{2}$$

where $y_i$ is the SNR value for the i observation (elevation angle) and $\dot{y}_i$ is the required SNR value [23,24]. The relationship between the quantity of data, $D$, the data rate, R, and the parameters for a single ground station pass is determined by [5]

$$D = R(FT_{max} - T_{initiate})/M \tag{3}$$

where $T_{max}$ is the maximum time in view, $F$ is the fractional reduction in viewing time due to passing at the central earth, $T_{initiate}$ is the time required to initiate a communication pass, and $M$ is margin needed to account for missed passes. For power consumption performance, an average of total power supplied to the transmitter per hour is calculated and discussed in the results section.

The ATCU model only has one input parameter, which is the elevation angle. The elevation angle ranges from 0° to 90°. The orbit propagator is available in the Attitude and Determination Control System (ADCS) subsystem and at the ground station mission control system. For the CubeSat application, the ADCS function resides in the satellite OBC. The elevation angle values for each pass can be produced by the orbit propagator. The mission control system at the ground station can further upload in advance the information of the elevation angle and transmitter turn-on time. This is normally done when the timing of the satellite OBC and the ground station are synchronised. Time synchronisations are periodically accomplished every two weeks.

Simulation using Systems Tool Kit (STK) software are performed to get more certain satellite contact duration, SNR and data throughput. The satellite orbit and ground station parameters for the satellite operation simulation are chosen based on the Tiga-U satellite bus mission [18]. The satellite orbit is configured using

RazakSAT orbiting parameters as a case study. RazakSAT offers 14 times of passes per day over Malaysia, which high frequency compared to a sun-synchronous orbit. NEqO orbit is selected as a case study not only because of a high number of passes but also because of big coverage countries along the equatorial region, proved by the TeLEOS-1, the first commercial NEqO satellite developed by Singapore [25,26]. The simulation parameters are keyed in for the one-year operational duration and configured for daily data collection. Fig. 3 shows the methodology of conducting a satellite operation simulation using STK. From the conducted simulation, total passes duration for 81,760 min per year are analysed as per listed in Table 3.

It is important to start the ATCU model from 5° elevation angle based on the results taken from the link budget analysis [18]. The data rate suitable for an elevation angle less than 15° is 9600 bps to limit the transmission power at 1 W or below. The selected data rate of 9600 bps is based on the typical usage by an amateur radio band and CubeSat [8]. By selecting this data rate, almost 50% of power consumption is saved compared to a selection of using a higher data rate which requires a 2 W RF transmit power. From the same link analysis, the RF transmit power is reduced up to 0.5 W for the elevation angles ranging between 10° to 14°. For elevation angles, more than 15°, the data rate of 19,200 bps is selected to optimise the amateur radio bandwidth and increase data capacity. The selections of RF transmit power for this data rate configuration employ the link margin guideline; the same approach as the data rate of 9600 bps. The complete configuration of the RF transmit power, data rate and elevation angle are shown in Table 4.

The ATCU controls the data rate and RF transmit power based on the elevation angle input. To reconfigure the outputs based on the elevation angle, each cycle for ATCU has a 60-second duration. The integration of ATCU and transmitter are also involved in the OBC and the Power System. A block diagram of the adaptive transmitter subsystem is shown in Fig. 4. The OBC allows the telemetry or payload data to be downloaded to the transmitter. The OBC also controls the ON/OFF status of the transmitter via a command to the power subsystem. When the satellite trajectory information is uploaded, it is stored and managed by OBC. The OBC further manages the trajectory information which includes the task schedules that trigger the transmitter's "ON" or "OFF" condition. Once the transmitter is turned on, the ATCU will decide the data and the RF transmitting power required. The transmitter with the adaptive function only requires elevation angle data input from OBC. The single input allows for easy integration with different satellite buses or payloads. Based on the elevation angle, the data rates are selected by ATCU. ATCU will select the RF transmitting power according to the configuration presented in Table 4.

**Table 3**
STK simulation output for 1 year operation.

| | | |
|---|---|---|
| Total passes | 81,760 | Year duration in minutes |
| | 4,905,600 | Year duration in seconds |
| Average passes | 224 | Daily average duration in minutes |
| | 13,440 | Daily average duration in seconds |
| Daily Pass Time | 15 | Min |

**Table 4**
Input and Output Configurations for the ATCU Model.

| Input Selection Elevation angle (°) | Output | |
|---|---|---|
| | Data rate (bps) | RF Transmit power (W) |
| 0–9 | 9600 | 1.0 |
| 10–14 | 9600 | 0.5 |
| 15–24 | 19,200 | 1.0 |
| 25–90 | 19,200 | 0.5 |

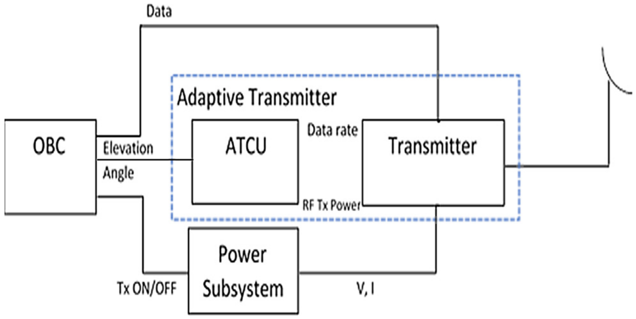

**Fig. 4.** Block diagram of adaptive transmitter sub-system.

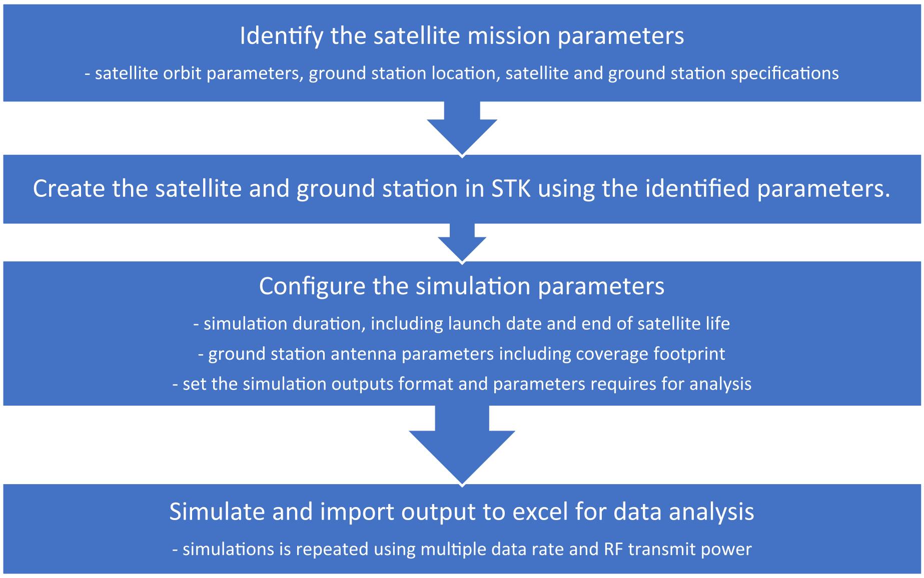

**Fig. 3.** The methodology of conducting a satellite operation.

## 3. Results and discussion

### 3.1. Adaptive transmitter functional test result

For the adaptive transmitter functional test, the transmitter is configured with input antenna elevation angles between 0° and 90° for the ATCU input. This configuration also includes the attenuator setup equivalent to the Free Space Loss (FSL) expected to be experienced by the transmitter in space. A single satellite pass is simulated using STK to obtain the in-orbit parameters, elevation angle, distance and FSL. The simulation results are listed in Table 5. From this table, the satellite pass begins with an elevation angle of 4° at the first minute and increases up to 69°. The transmission distance and FSL reduce when the elevation angle increases. As the satellite rises above the horizon, the elevation angle increases from 0° to 69° on the seventh minute. Starting from the eighth minute of the satellite pass, the elevation angle is 64° and begins reducing to 0°. When the antenna elevation angle reduces, the transmission distance and FSL increase and are inversely proportional to the antenna elevation angle input.

In this test, three important measurements are evaluated: the SNR, power consumption and data capacity. Based on Table 5, the SNR outputs at different antenna elevations within 15 min of a typical satellite pass are plotted. The SNR results using the ATCU model configuration, described in Table 4 as the developed adaptive transmitter (DAT), are plotted in Fig. 5. The SNR measurement results are compared to the required SNR for the FSK modulated signal. The required SNR was set to 16.3 dB, which is equivalent to 13.3 dB for the required SNR for the FSK modulation, with a margin of 3 dB [5].

**Table 5**
Single Pass Satellite Operation Simulated Output for Elevation Angles and FSL.

| Satellite Pass | Elevation Angle (°) | Distance (km) | FSL (dB) |
|---|---|---|---|
| 0:00 | 0 | 3013 | −155 |
| 0:01 | 4 | 2635 | −154 |
| 0:02 | 8 | 2257 | −152 |
| 0:03 | 13 | 1884 | −151 |
| 0:04 | 20 | 1521 | −149 |
| 0:05 | 30 | 1181 | −147 |
| 0:06 | 46 | 889 | −144 |
| 0:07 | 69 | 712 | −142 |
| 0:08 | 64 | 737 | −143 |
| 0:09 | 42 | 949 | −145 |
| 0:10 | 27 | 1256 | −147 |
| 0:11 | 18 | 1604 | −149 |
| 0:12 | 12 | 1970 | −151 |
| 0:13 | 7 | 2345 | −153 |
| 0:14 | 2 | 2724 | −154 |
| 0:15 | 0 | 2986 | −155 |

During the test, in the transition from 10° to 15°, the RF transmit power reduced from 1 W to 0.5 W. By reducing the transmit power to 0.5 W at 10° elevation angle, the SNR value is optimum. However, the transmit power increased back to 1 W when the elevation angle was between 15° and 20°. This simplified model is plotted as the simplified adaptive transmitter (SAT) in Fig. 5. Despite improving efficiency, this rapid change in power transmission could be simplified by maintaining the RF transmit power at 1 W. By doing so, the transient effect and stability of the transmitter frequency are maintained. The SAT reduces complexity and the SNR performs optimally compared to the fixed transmitter with extra power required. By adopting this new configuration, the SNR is less optimum by 3 dB and power consumption is increased by 0.8 W. The advantage of this simplified model is that the transmitter can be maintained at 1 W for any elevation angle between 0° and 24° and only reduces to 0.5 W for elevation angles between 25° and 90°. By reducing the frequency of changing output power levels, the amplifier stability and reliability are increased.

The power consumption and data capacity results for DAT are listed in Table 6, together with the SNR results based on the elevation angle input. The selection of data rates and RF transmit power are based on the ATCU model. The measured RF transmit powers are as per the expected output according to the model designed and within the ±0.5 dBm range. The data capacity per minute results have 0.066 Mbyte for the data rate of 9,600 bps, and 0.132 Mbyte for the data rate of 19,200 bps. The results indicate that the data capacity is almost consistent with around 55 s occupied for data transmission. The DAT data collected are compared with the measured fixed transmitter data and other sources.

### 3.2. Adaptive and fixed transmitter performance comparison

The transmitter selected as the fixed transmitter is AX100-U, manufactured by GomSpace Inc. and used in several CubeSat missions such as RANGE (The Ranging and Nanosatellite Guidance Experiment), NASA USIP (Undergraduate Student Instrument Project) and SEAM (Small Explorer for Advanced Missions) [27]. The

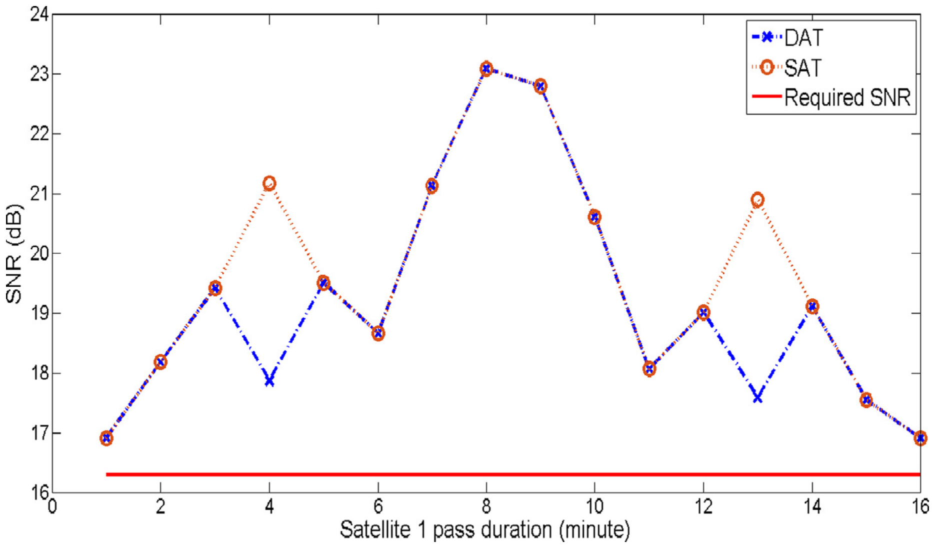

**Fig. 5.** SNR measurement results for the developed adaptive transmitter and simplified adaptive transmitter.

**Table 6**
Summary of DAT Functional Test Results.

| Input Selection | Output Selection | | | Adaptive Transmitter Output | | |
|---|---|---|---|---|---|---|
| Elevation angle (°) | Data rate (bps) | RF Transmit power (W/dBm) | | Data capacity/ minute (Mbyte) | RF Transmit Power (W/dBm) | Power Consumption (W) |
| 0–9 | 9600 | 1.0 | 30.0 | 0.066 | 30.5 | 2.3 |
| 10–14 | 9600 | 0.5 | 26.7 | 0.066 | 27 | 1.7 |
| 15–24 | 19,200 | 1.0 | 30.0 | 0.132 | 30.4 | 2.3 |
| 25–90 | 19,200 | 0.5 | 26.7 | 0.132 | 26.5 | 1.7 |

AX100-U transmitter is a reconfigurable transmitter in which data rates can be selected based on the satellite mission requirement. The transmit power for this transmitter was fixed at 1 W, as recommended by the manufacturer and published on their website. This commercial CubeSat transmitter has the capability to transmit from +26 dBm to +30 dBm but is only applicable by changing the transmission frequency [28]. During transmission, the RF transmit power has the same accuracy as the adaptive transmitter, which is ±0.5 dBm. With these transmitter specifications, the AX100-U was selected as the fixed transmitter and evaluated at two different data rates; 9600 bps and 19,200 bps.

The AX100-U transmitter is an example of an available transmitter that could be integrated with the ATCU model, with some adjustments to the transmit power function. The transmitter is denoted as Fixed1 for AX100-U with a data rate of 9600 bps, and Fixed2 with a data rate of 19,200 bps. In Tables 7 and 8, the transmitter specifications for both fixed and adaptive transmitters are listed.

DAT performances are measured using the wired End-to-End test setup. This test setup involves integration modules from OBC, power subsystem and ground station system [29]. The FSL of each minute of the satellite pass is represented using attenuators with the same power loss value. The measured SNR from the developed prototype is used and compared to the AX100-U measured SNR results [28]. In order to acquire a comprehensive comparison, different types of adaptive models are also considered. Additional data from the SDR transmitter developed by Aerospace Corporation [15] are plotted as Aerospace Adaptive Transmitter (AAT) with other SNR results in Fig. 6. The difference between the ATCU model and the adaptive model developed by the Aerospace Corporation is the parameters involved in the models. In the ATCU model, the multiple data rate and RF transmit power are configured to achieve optimum SNR; but in the AAT model, multiple modulation techniques are used. The type of modulation techniques and data rate range are also different between these models. The AAT model employs phase shift keying (PSK) and has a lower threshold for the required SNR compared to the ATCU model which uses FSK.

**Table 7**
Fixed1 and Fixed2 Transmitter Specifications.

| Item | Specification |
|---|---|
| Frequency | 437 MHz (UHF band) |
| Transmit Output Power | 1 W |
| Data rate | 9.6 kbps, 19.2 kbps |
| Phase Noise at 1 MHz offset | −120 dBc/Hz |
| Spurious | −70 dB |
| ACPR | −45 dB |
| Power Supply | 3.3 V |
| Current (max) | 0.8 A |
| Power Consumption | 2.6 W |

**Table 8**
Developed Adaptive Transmitter (DAT) Specification for ATCU Model.

| Item | Specification |
|---|---|
| Frequency | 437 MHz (UHF band) |
| Transmit Output Power | 0.5 W @ 1 W |
| Data rate | 9.6 kbps, 19.2 kbps |
| Phase Noise at 10 kHz offset | −100 dBc/Hz |
| Spurious (dBc/Hz) | −65 dBc/Hz |
| ACPR | −30 dB |
| Power Supply | 3.3 V, 5 V |
| Current (max) | 0.46 A |
| Power Consumption | 1.7 W, 2.3 W |

Three aspects have been evaluated and compared between DAT, AAT and the fixed commercial transmitter. The first aspect considered is the performance of SNR optimisation. For the second aspect, the data capacity performance is analysed. The third aspect is the power efficiency performance which involves the RF transmit power and power consumption. The AAT model is excluded from the second and third aspect analyses since it employs a different frequency band which allows for higher data rate transmission; the details of power consumption results are not available.

From Fig. 6, the required link SNR for FSK with 3 dB margin is set at 16.3 dB and comply with both the fixed and developed adaptive transmitters, except for Fixed2 Tx. The required link SNR for AAT is less compared to other transmissions since PSK modulation techniques are used. The required SNR for PSK with 3 dB margin is set at 13.6 dB. The Fixed2 Tx only complies with the link margin requirement for elevation angles of more than 10°. This is due to the limitation of using fixed transmit power at 30 dBm. This condition limits the contact duration during satellite passes and reduces data capacity performance.

In order to evaluate the SNR optimisation performance, the required SNR is taken as the optimum value of any transmission, and variability values compared to this threshold are considered as errors or more accurate as RSME. The RMSE of each method is calculated using Eq. (2) and plotted in Fig. 7. Based on the analysis, DAT has the lowest RMSE, 3.4, while Fixed Tx2 has the highest RMSE, 6.84, followed by AAT with 6.81. Even though DAT and AAT techniques are an adaptive transmission, by adopting a different configuration model, the percentage of RMSE performance produced a 101% difference. By comparing fixed and adaptive performances, the Fixed1 Tx has a additional 41% RMSE compared to DAT.

The second aspect evaluated is data capacity performance. The data capacity is assessed by multiplying the data rates with the time taken in an available pass. The data capacity is then converted to Bytes. The adaptive rate is evaluated with Fixed1 and Fixed2 transmitters and the results are plotted in Fig. 8. The Fixed1 fully occupied the full-time duration of 15 min in one satellite pass, while Fixed2 only occupied 11 min of the transmission duration due to the increase in elevation angle. The adaptive transmitter has the advantage of using the full-time duration of a satellite pass for data downlink; at the same time, it applies a higher data rate when the elevation angle permits.

The total throughput for Fixed1 and Fixed2 are 1.056 Mbytes and 1.32 Mbytes, respectively. These amounts for data capacity are less than DAT's capacity, which is 1.584 Mbytes. The results

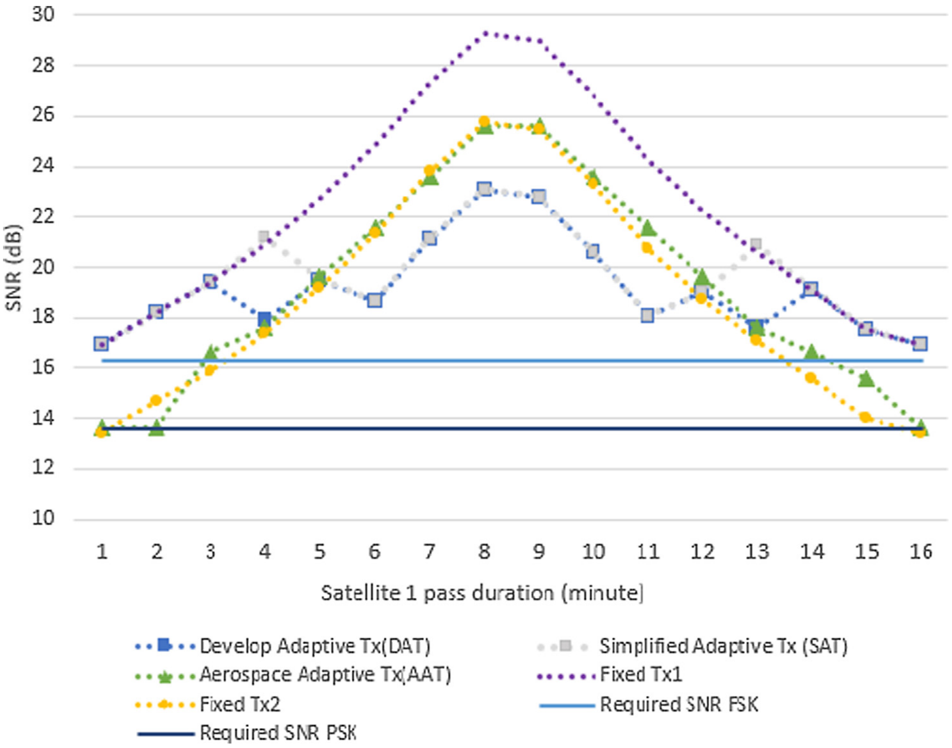

**Fig. 6.** Measured SNR for fixed and adaptive transmitters in 1 satellite pass per minute.

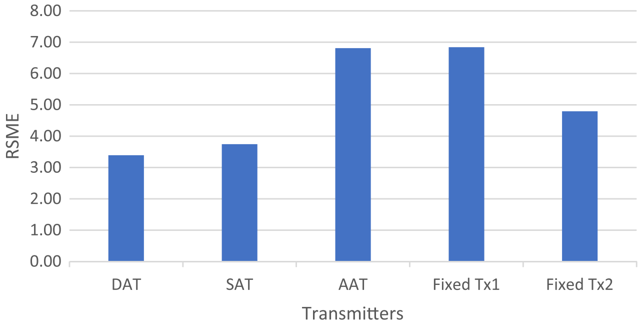

**Fig. 7.** RMSE value for fixed and adaptive transmitters SNR performance.

show that DAT has a data capacity of 50% more compared to Fixed1 and 20% more compared to Fixed2. DAT has the advantage of using the complete satellite pass duration for data downlink; at the same time, it uses a higher data rate solution. The third performance evaluated for the developed transmitter is power consumption. The power consumption depends on the RF transmitting power. By reducing the RF transmit power, the total power consumption will be reduced. The power consumption measurement results for the fixed and DAT are plotted in Fig. 9. Fixed1 and Fixed2 are transmitting at the same output, 30 dBm (1 W), and have the same power consumption, 2.6 W. Both Fixed1 and Fixed2 use the Fixed Tx label.

The fixed transmitter has constant value; 30 dBm RF transmit power and 2.6 W power consumption in satellite 1 pass duration.

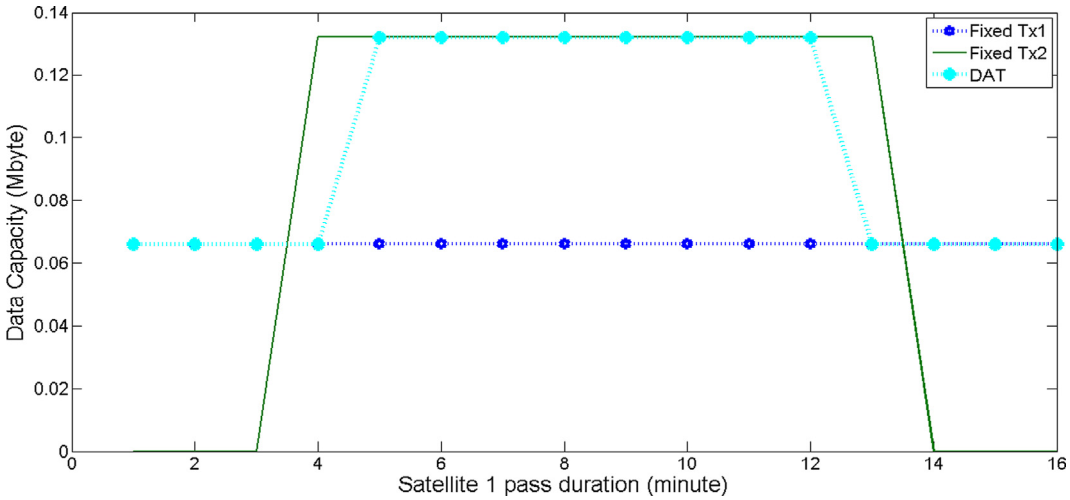

**Fig. 8.** Data capacity results for fixed and adaptive transmission.

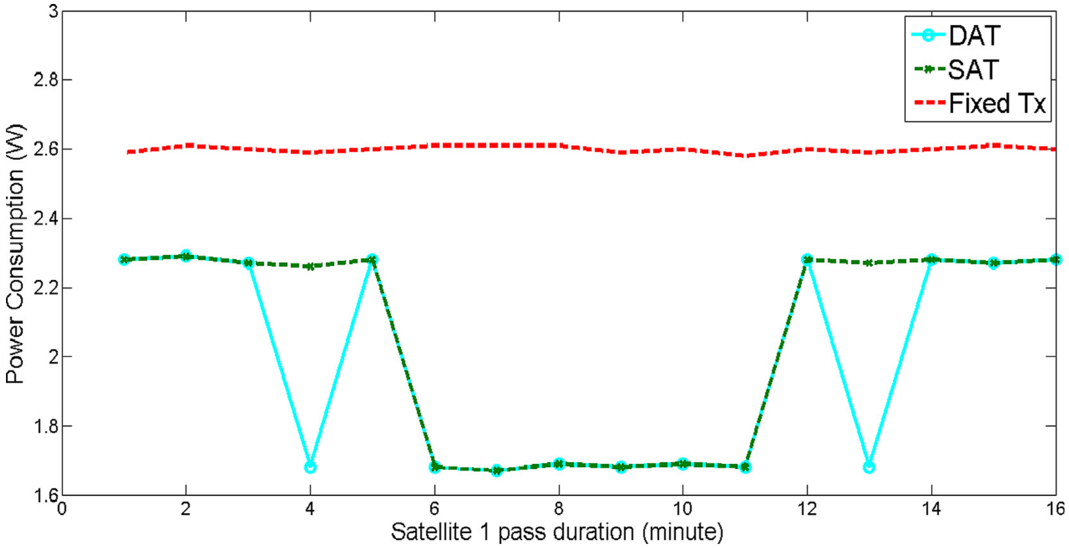

**Fig. 9.** Power consumption results for DAT, SAT and fixed transmission.

**Table 9**
Summary of DAT Performance Compared to Other Transmitters.

| | **DAT** | SAT | AAT | Fixed1 Tx | Fixed2 Tx |
|---|---|---|---|---|---|
| RMSE SNR | 3.39 | 3.75 | 6.81 | 6.84 | 4.79 |
| – Additional error compared to DAT (%) | | 9.5 | 101 | 102 | 41 |
| Data Capacity (Mbyte) | 1.584 | 1.584 | – | 1.056 | 1.32 |
| – Additional DAT Data (%) | | – | | 50% | 20% |
| Power Consumption (W/h) | 8.4 | 8.8 | – | 11.1 | 11.1 |
| – Additional power compared to DAT (%) | | 3.7 | | 31 | 31 |

Meanwhile, DAT is configured each minute, based on the ATCU model. The DAT result is plotted in Fig. 9 with the SAT and fixed transmitter results. The SAT model reduces the number of RF transmit power changes and increases stability to the output power. Based on the measurement results, the power consumption for each transmitter is calculated in W/hour. The fixed transmitter employs 31% power consumption compared to DAT. As expected, the SAT requires more power compared to DAT with an additional 3.7%. Based on the three performance evaluations, the developed adaptive transmitter improved the SNR optimisation, data capacity and power consumption compared to the fixed and adaptive transmitter. Table 9 lists the developed adaptive performance compared to other transmitters.

## 4. Conclusion

An adaptive transmitter for CubeSat with transmitting power and data rate control function is designed and developed in this work. This paper focuses on the design and analysis of the adaptive model unit, hardware development as well as functional and compatible test validations. The relationship between the RF transmit power, received antenna elevation angle and data transmission rate are established using the link budget analysis and satellite operation considerations. Based on these analyses, the ATCU model for the transmitter is designed. The adaptive transmitter is also tested and demonstrated to work in the lab environment. The performance of the SNR optimisation is improved compared to a fixed commercial transmitter from GomSpace and an adaptive transmitter from the Aerospace Corporation. By adopting the ATCU model, the results indicate potential improvement in performance in terms of SNR, power consumption and data throughput. The adaptive function of this transmitter will be the design foundation for future types of CubeSat transmitters and even larger satellites operating in LEO.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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