Improved Power Control Approach for Better Data Throughput in CubeSat Nanosatellites

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***Abstract*—Adaptive/Variable Coding and Modulation (ACM/VCM) techniques have been used to enhance the data throughput of CubeSat nanosatellites with limited resources and communication capabilities. On average, these techniques showed an improvement by almost doubling the data throughput over the traditional fixed modulation method. To move beyond that, we seek to further enhance the performance of the VCM/ACM techniques by considering the CubeSat's power features. Altering the power level is a key contributor in the process of selecting the suitable modulation and coding option of the VCM/ACM techniques. In this paper, we introduce our approach named "Improved Power Control" (IPC), which is based on the combination of Adaptive Coding and Modulation (ACM) and Adaptive Power Control (APC) techniques. Simulation studies are performed on a sample remote-sensing CubeSat mission that takes photos from the payload camera and sends them to the ground station. Performance comparison of the three modulation techniques (fixed modulation, ACM, and IPC) is carried out with respect to the total data throughput and the total number of photos that can be downloaded from the CubeSat. The results show that the IPC approach, which considers the CubeSat's power feature while applying the ACM technique, outperforms the simple fixed methods by a wide margin. When compared to the ACM method deployed alone, IPC offers 35% more data throughput and 80% more photos downloaded in the said remote-sensing CubeSat mission.**

***Index Terms*—CubeSat, satellite communication, adaptive code modulation, adaptive power control**

I. Introduction

A CubeSat (strictly speaking a 1U-CubeSat) is a nanosatellite with the dimensions 10cm×10cm×10cm and a maximum weight of 1.33kg. It is designed with very limited specifications to emulate the potentials of large satellites at a lower cost. This feature allowed budget-constrained entities such as schools and universities to build their CubeSats and conduct their space-related researches. With the growth of such CubeSat missions, the need for having high data throughput became essential to get as much as possible from the collected data.

However, various factors restrict the CubeSat data throughput. One of the main limitations is the few available short communication windows during the life of the CubeSat mission. Another constraint is the CubeSat's small size. It restricts the use of large solar panels and a powerful antenna system which are strongly associated with the strength of the transmitted signal.

In the literature, many solutions have been proposed to enhance the CubeSat communication subsystem. Some focused on the physical improvements of the communication subsystem's components such as proposing a new design for the CubeSat antenna and transceiver. However, these types of improvements require building new products, whereas, in typical educational CubeSat missions, the components are taken from the off-the-shelf products. For this reason, we focus on studies that proposed improvements based on the specifications of the available off-the-shelf components of the CubeSat. These studies concentrated more on the aspects of CubeSat communication subsystem like improving the communication protocols, coding algorithms, modulations, etc. One of the prominent studies resulted in high data throughput based on the Variable/Adaptive Coding and Modulation (VCM/ACM) techniques [1], [2]. However, these techniques focus only on altering the modulation without taking advantage of the CubeSat's variable power feature.

Usually, in the CubeSat missions, the common practice in calculating the power budget relies on the worst case scenario of the power subsystem in order to ensure the power availability during the whole mission life. At the same time, this is a waste of the power, especially by taking into consideration the best case scenario of the power subsystem where the power generation at the maximum. The excess power capacity can be used to increase the transmission power and thus enhance the performance of VCM/ACM techniques. Therefore, in our research, we introduce our new *Improved Power Control (IPC)* approach, which is a combination of ACM and Adaptive Power Control (APC) techniques, where APC is designed to suit the CubeSat's power limitations.

Measuring the performance of our approach was carried out through simulation using AGI's Systems Tool Kit (STK) [3] on a sample CubeSat, namely MySat-1 [4]. Its mission is to perform remote sensing in which photos of a certain region of the earth are taken from the payload camera and sent to the ground station. The specifications of this sample CubeSat mission were used to measure the total data throughput of three communication scenarios. For the first scenario, we simulated a communication link using the fixed modulation method. For the second scenario, we examined the ACM method. For the third scenario, we investigated our new IPC approach. The total data throughput of the three scenarios were quantified and compared.

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This paper is a summary version of the master's thesis of the first author [5].

II. Background

A. CubeSat Communication Subsystem

A CubeSat is typically composed of (i) the payload subsystem (PAY), (ii) the communication subsystem (COM), (iii) the on-board computer subsystem (OBC), (iv) the attitude determination and control subsystem (ADC), (v) and the electrical power supply subsystem (EPS).

The communication subsystem (COM) consists of two main components: the transceiver and the antenna. The transceiver is a combination of the transmitter (TX) and receiver (RX). The responsibility of the COM subsystem is to provide a reliable and continuous communication channel between the ground station and the CubeSat. For any communication channel, the basic link budget [6] should be calculated to ensure the link availability between two entities using their communication specifications.

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} + G_{RX} - L_{RX} - L_M \quad (1)$$

The received power (P_{RX}) at the receiver side is calculated by adding the transmitted power (P_{TX}) of the transmitter, the antenna gain (G_{TX}) of the transmitter, and the antenna gain of the receiver (G_{RX}), and then subtracting from them the free space path loss (L_{FS}), transmitter losses (L_{TX}), receiver losses (L_{RX}) and any other losses (L_M) such as atmospheric losses. The measurements are in dB. Eventually, receiving a signal at a high power reflects positively to the amount of data rate that is required to send any type of data from a CubeSat such as high-resolution pictures in a remote-sensing mission.

P_{RX} can be expressed using the link margin formula [6] which is based on the signal-to-noise ratio (SNR) .

$$SNR = (E_s/N_0) \cdot (R_s/B) \quad (2)$$

where E_s is the energy per symbol, N_0 is the one-sided noise spectral density, R_s is the symbol rate, and B is the noise bandwidth.

The greater link margin value, the stronger the signal. Thus, better modulation can be used to transfer more data. The link margin is affected by different factors where some are not controllable like the free space path loss and atmospheric losses, while some others are under control like using a powerful antenna at the ground station. However, most of these factors lead to considerable consequences like increasing the mission cost. For large space missions with sizable monetary budgets, this may not be a big issue. But, for low-cost missions like an educational CubeSat, this becomes a serious issue.

B. CubeSat Communication Protocols

Multiple studies focused on maximizing the data throughput by using high-performance communication protocol. One of the most leading protocols in space communication is based on the Variable coding and modulation (VCM) and the Adaptive Coding and Modulation (ACM) techniques. The fundamental idea of these techniques is the dynamic changing of the signal modulation and coding options by depending on the condition of the communication link in order to increase the link throughput, reliability, and efficiency. When the link condition is good, high-order modulation and coding schemes with low overhead are used to achieve high throughput and the converse when the link condition is bad [1], [2]. At CubeSat level, the same method was applied to increase the total data throughput by choosing higher modulation and coding option when the power level of the received signal is increased as a function of the free space path loss. More specifically, the path loss between the CubeSat and the ground station is reduced at the times when the former is moving closer to the latter.

Another useful communication approach is Adaptive Power Control (APC). This approach has been used in geosynchronous satellites as a fade mitigation technique [7]. The main concept is to increase the uplink signal strength by supplying it more power from the ground station equipment. This in turn leads to rise the downlink signal strength.

By combining up the advantages of the two approaches, an improvement to the overall CubeSat throughput can be gained. The total data throughput of the ACM/VCM techniques is directly affected by the received signal power. Receiving a higher signal level than the normal one will allow the ACM/VCM techniques to select higher modulation and coding options. Consequently, higher data throughput will be achieved.

In our research, we design an improved power control mechanism to suit the CubeSat power capability and at the same time contributing to increasing the total data throughput.

III. Related Work

There are much research works which investigated the use of VCM/ACM techniques for satellite communications. As the CubeSat is our main target, we focus on the ones that investigated the use of VCM/ACM techniques on CubeSats and summarize them as follows.

A study conducted by Sielicki [6] was on improving the total CubeSat data throughput by utilizing the VCM protocol. The suitable modulation and coding scheme is selected based on determining the mode that can operate at the E_s/N_0 of the received signal. The approach was tested using Matlab simulation, and the results showed that the total data throughput was doubled.

Downey et al. [8] conducted a study on the VCM modulation using NASA's space communication and navigation testbed. Evaluating the performance of the VCM technique was based on a comparing the overall data throughput of VCM and the standard performance of the NASA waveforms. The experimental results showed that on average, the VCM technique performed better than the standard NASA waveform by 2.7dB.

Other previous studies conducted by the same team (Downey et al. [9]) and AGI's STK [3] proved the effectiveness of the VCM/ACM techniques on the CubeSat data throughput.

To the best of our knowledge, none of the previous CubeSat studies have utilized the power feature in their VCM/ACM approaches.

IV. Proposed Improved Power Control (IPC) Approach

The objective of the proposed Improved Power Control (IPC) approach is to increase the output power of the transmitted signal whenever there is excess energy. The main component of IPC is the *power control function* (Equation 3). It is an equation that calculates the amount of power that should be used by the communication subsystem. This is done by subtracting the quantity of the summation of the total power consumption during the operation of downloading data, and the safety power capacity defined by the CubeSat operator from the available power capacity of the EPS subsystem.

$$Power_{Margin} = EPS_{Ap} - (Operation_{En} + Safety_{En}) \quad (3)$$

where $Power_{Margin}$ is the power capacity that can be used by the communication subsystem, EPS_{Ap} is the available EPS's power capacity during an orbit pass, $Operation_{En}$ is the energy consumption of the CubeSat's components during the operation of downloading data (like photos in a remote-sensing CubeSat mission), and $Safety_{En}$ is the power capacity used for safety reason per one orbit pass. All terms are in mWh.

Now, we will describe how our IPC approach works using the following scenario.

In order to apply the power control approach, few instructions are required. First, the equation is only used when the transmit mode of the photo downloading operation is on. Second, the CubeSat on-board computer should have the following: the value of the safety power capacity, the initial power consumption's value of the CubeSat components for the operation of downloading photo, the function of the power control, and a function to measure the available power capacity within the EPS subsystem. Besides, the CubeSat transceiver should be programmed with various modulations based on the mission MODCODs (modulation and coding options). Likewise, the ground station should have a pre-defined list of MODCODs with their required E_b/N_0 (energy per bit to noise power spectral density ratio). Also, the ground station software should have the required function for applying the ACM approach.

When the ground station starts receiving the CubeSat beacon, the ground station will send a command to the CubeSat to use the power control function. If the result is positive, the transceiver output power will increase by a command from the on-board computer. Otherwise, no change will be made. At the ground station, the E_b/N_0 of the received signal will be calculated and used to select the suitable MODCOD option from the pre-prepared set of MODCODs. After selecting the suitable MODCOD, the ground station will command the CubeSat to change the MODCOD. This process will be repeated until the end the communication window. After each operation of downloading data, the CubeSat should reset the output power of the communication subsystem to its initial value.

TABLE I
CubeSat's MODCODs used in our experiment

Modulation Name	BER	Required E_b/N_0 (dB)	Data Rate (bps)
QPSK	10^{-5}	12.8	(11200–20800)
8PSK	10^{-5}	17.9	(21600–31200)
16QAM	10^{-5}	20.2	(32000–41600)
64QAM	10^{-5}	27	(42400–62400)
256QAM	10^{-5}	33	(63200–83200)

For our study, we use the MODCODs presented in Table I.

V. Experimental Case Study

A. Case Study CubeSat

Our case study will be based on the operational simulation of a sample remote-sensing CubeSat mission called *MySat-1* [4], which is developed by Masdar Institute (a part of Khalifa University of Science and Technology), Abu Dhabi, United Arab Emirates. It is planned to be launched in the last quarter of 2018. It will take the photos of the geographical region United Arab Emirates and send them to the ground station. For our case study, we will assume the following:

- The CubeSat orbit specifications are same as the International Space Station (ISS) ones.
- The location of the ground station is in Abu Dhabi, United Arab Emirates.
- The mission period is six months.
- The CubeSat frequency is UHF, and the default modulation is QPSK.
- The CubeSat subsystems are the payload subsystem (PAY) (which is a camera), the communication subsystem (COM) (whose subcomponents are the transmitter, TX, and the receiver, RX), the on-board computer subsystem (OBC), attitude determination and control subsystem (ADC), and the electrical power supply subsystem (EPS) (using solar panels and a battery).

In most CubeSat missions, three modes are mainly used the deployments mode, the safe mode, and the normal operation mode [10]. In our case study, we will only consider the normal mode, in which most of the CubeSat operations are performed within it. This mode corresponds to the highest level of the power consumption since most subsystems perform their normal tasks during it. We assume that the following operations will be performed during the normal mode of the mission.

- Taking photos using the payload camera.
- Downloading the photos to the ground station by using the communication subsystem.

For the initial power consumption calculation, we assume that each of the above operations will be performed independently per orbit. Therefore, we will consider only the power consumption during the operation of downloading data since our focus on the communication subsystem.

For the detailed power analysis, the CubeSat system energy capacity, its energy consumption, and the link budget are

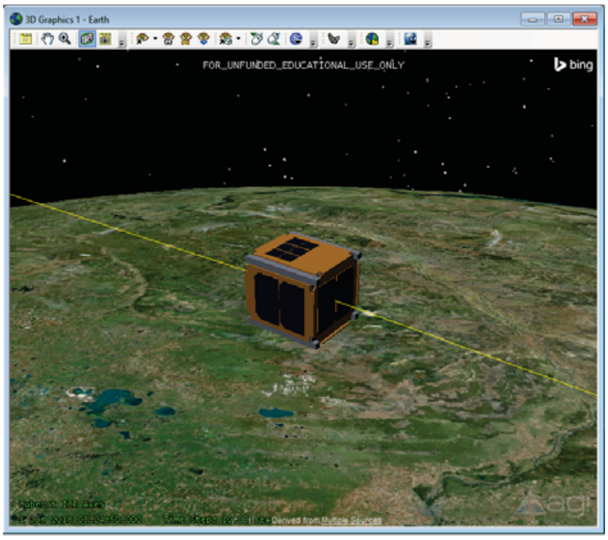

Fig. 1. Snapshot from CubeSat's power analysis in STK

calculated. However, those formulas are omitted from this paper due to the page limit. Interested readers can refer to Section 3.3.4 of the master's thesis of the first author [5].

B. Experimental Setup

To validate our approach, we will compare its performance with those of fixed modulation and ACM through simulations. We name the three competitors as follows.

1) Case-1: Fixed modulation (using QPSK),
2) Case-2: Adaptive Coding and Modulation (ACM), and
3) Case-3: Improved Power Control (IPC) (our proposed method)

The evaluation criteria will be based on the following three perspectives.

- The total data throughput in a communication window.
- The total number of photos that can be downloaded in a communication window.
- The total number of photos that can be downloaded in the whole CubeSat mission.

Again, the detailed parameters and calculations involved in these evaluation criteria are omitted from this paper due to the page limit. Interested readers can refer to Sections 3.3.1–3.3.3 of the master's thesis of the first author [5] as well.

The Systems Tool Kit (STK) software [3] developed by AGI is extensively used in our simulations.

VI. Experimental Results

A. CubeSat Power Generation

After simulating the power generation analysis for the whole mission period of our case study CubeSat in STK [3] (Figure 1), we got the power generation levels in shown in Figure 2.

From the results, we calculated the minimum, maximum, and average energy levels. We excluded the data from the Eclipse period because no power generation could be made

Fig. 2. CubeSat power generation analysis during six months period of time (simulated by STK)

TABLE II
Actual power consumptions of CubeSat subsystems

Power (mW)	EPS	OBC	COM (TX)	COM (RX)	Total
Required power	15	900	5000	3800	9715
Consumed power (with 10% loss)	16.6	1000	5555.55	4222.2	10794.35

during this period. The results are: Minimum = 2243 mWh, Average = 3066 mWh, and Maximum = 3343 mWh.

By using the minimum energy level and the battery energy capacity, the total energy level available for use by the CubeSat components is equal to:

Total Energy capacity (mWh) = Solar panel energy generation (mWh) + Battery energy capacity (mWh) = 2243 + 11000 = 13243.

B. CubeSat Energy Consumption

The energy consumption is calculated by multiplying the power consumption and the time duration. For the power consumption, we applied the loss equation in pg. 35 of [5] assuming 10% loss to the components power consumption and we got the results in Table II.

For the operation time duration for each subsystem, we used STK to compute it and got the measurements shown in Table III. From them, using the pre-defined energy equations in pg. 36 of [5], we calculated the total energy consumption for one orbit pass, which are also given in Table III).

C. Total Data Throughput per Communication Window

After simulating the three methods, namely, (i) fixed modulation with QPSK (Case-1), (ii) ACM (Case-2), and (iii) IPC

TABLE III
Simulated operation time and energy consumption of subsystems for one orbit pass

Subsystem	Time duration (m)	Energy consumption (mWh)
EPS	96.1	26.69
OBC	96.1	1601.67
COM (TX)	16.4	1518.52
COM (RX)	96.1	6762.59
Total		9909.47

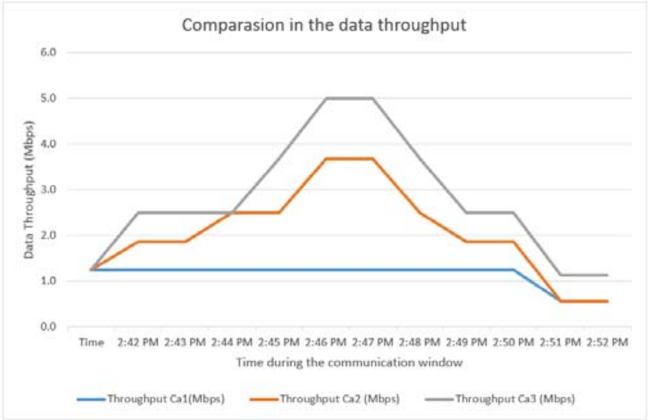

Fig. 3. Comparison in the data throughput amount among the three cases

(Case-3), we got the following results respectively.

For the Case-1 results (see Table IV(a)), we can see that the data throughput amount is constant during the whole communication period, while there is a very good margin, especially at the mid duration. This is really a waste of the link margin, specially, in the case of CubeSat missions where the communication window is too short to download the mission's data. The reason is that the extra amount of the margin could be used to assign higher modulation for the communication link and thus obtain higher data throughput, but the simple fixed modulation approach failed to do so.

The data throughput of Case-2 (see Table IV(b)) is variable. Furthermore, we can observe the change in the value of the data throughput in conjunction with the change in the value of the margin. Thereby, we utilized the whole benefit of the link margin by applying the ACM technique.

Finally, using our proposed IPC approach, the data throughput of Case-3 (see Table IV(c)) is variable and is further improving with the growth of the link margin value. Thus, the benefit of the link margin is fully utilized.

As can be seen from Figure 3, the total data through of Case-2 is higher than that of Case-1. On the other hand, the total data through of Case-3 is even higher than that of Case-2. Case-3 enjoys the data throughput with increases of 145% compared to the fixed modulation and 35% compared to the standard ACM modulation.

D. Total Number of Photos Downloaded per Communication Window

The results of the total number of photos in a communication window (Table V) were obtained after applying the required calculations in Section 3.3.2 of [5].

As shown in Table V, by using the fixed modulation approach, three photos can be downloaded per a communication window. For Case-2, it is possible to download five photos per a communication window which is a nearly double the number of photos in Case-1. However, IPC moved beyond that and allowed for downloading nine photos per one communication window which nearly double the number of photos in Case-2. As a result, our IPC approach achieved the best results with an improvement rate of 200% compared to fixed modulation and 80% compared to ACM.

E. Total Number of Photos Downloaded in Entire CubeSat Mission

By using the equations in Section 3.3.3 of [5], we calculated the total number of photos that can be downloaded during the period of our case study CubeSat mission, which is 6 months. The results are presented in Table VI.

As can be seen from the results, Case-3 (IPC) offers in the highest number of photos downloaded per the whole CubeSat mission, with 3546 photos in total. Since this is just a linear projection of the number of photos downloaded per communication windows in the above Section VI-D, the performance increases of IPC over fixed modulation and ACM are the same (i.e., 200% and 80% respectively).

VII. Conclusion

In this paper, the Improved Power Control (IPC) approach was introduced to enhance the data throughput of the CubeSat communication subsystem. The main role of the approach based on increasing the transmission power whenever there is an excess power capacity in the CubeSat power subsystem. Simulations on a case study remote-sensing CubeSat was used to validate the performance of our approach against those of the existing leading techniques used in the CubeSat Communication, namely, fixed modulation and ACM. The results demonstrate that in terms of total data throughput, IPC offers 145% and 35% increases over fixed modulation and ACM respectively. Regarding the total number of photos transmitted to the ground stations in a communication window or the whole mission, IPC enjoys even better results with 200% and 80% more photos sent compared to those two methods respectively. We hope our proposed IPC method will be useful for all future CubeSat missions with limited resources and power budgets by enabling them to achieve their optimal data throughput.

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TABLE IV
TOTAL THROUGHPUT FOR (A) CASE-1: FIXED MODULATION (WITH QPSK), (B) CASE-2: ADAPTIVE CODING AND MODULATION (ACM), AND (C) CASE-3: IMPROVED POWER CONTROL (IPC)

(a)

Duration (sec)	Ranges (km)	Losses (dB)	G/T (dB/k)	Occ BW	C/N (dB)	Eb/No (dB)	Required Eb/No (dB)	Margin (dB)	Mod	Throughput (bps)
60	2284.4	156.9	-8.76	24960	20.5	21.2	12.8	8.44	QPSK	1248000
60	1871.1	155.2	-8.76	24960	22.2	23.0	12.8	10.18	QPSK	1248000
60	1457.6	153.0	-8.76	24960	24.4	25.1	12.8	12.35	QPSK	1248000
60	1052.9	150.2	-8.76	24960	27.2	28.0	12.8	15.17	QPSK	1248000
60	676.7	146.3	-8.76	24960	31.0	31.8	12.8	19.01	QPSK	1248000
60	418.7	142.1	-8.76	24960	35.2	36.0	12.8	23.18	QPSK	1248000
60	512.03	143.9	-8.76	24960	33.4	34.2	12.8	21.43	QPSK	1248000
60	847.5	148.3	-8.76	24960	29.1	29.9	12.8	17.06	QPSK	1248000
60	1241.6	151.6	-8.76	24960	25.7	26.5	12.8	13.74	QPSK	1248000
60	1652	154.1	-8.76	24960	23.3	24.1	12.8	11.26	QPSK	1248000
27	2067.7	156.0	-8.76	24960	21.3	22.1	12.8	9.31	QPSK	561600
27	2256.4	156.8	-8.76	24960	20.6	21.3	12.8	8.55	QPSK	561600
Total (bps)										13603200
Total (Mbps)										13.6

(b)

Duration (sec)	Ranges (km)	Total losses (dB)	G/T (dB/k)	Occ BW	C/N (dB)	Eb/No (dB)	Required Eb/No (dB)	Margin (dB)	Mod	Throughput (bps)
60	2284.4	156.9	-8.76	24960	20.5	21.2	12.8	8.44	QPSK	1248000
60	1871.1	155.2	-8.76	24960	22.2	23.0	12.8	10.18	8PSK	1872000
60	1457.6	153.0	-8.76	24960	24.4	25.1	12.8	12.35	8PSK	1872000
60	1052.9	150.2	-8.76	24960	27.2	28.0	12.8	15.17	16QAM	2496000
60	676.7	146.3	-8.76	24960	31.0	31.8	12.8	19.01	16QAM	2496000
60	418.7	142.1	-8.76	24960	35.2	36.0	12.8	23.18	64QAM	3684000
60	512.03	143.9	-8.76	24960	33.4	34.2	12.8	21.43	64QAM	3684000
60	847.5	148.3	-8.76	24960	29.1	29.9	12.8	17.06	16QAM	2496000
60	1241.6	151.6	-8.76	24960	25.7	26.5	12.8	13.74	8PSK	1872000
60	1652	154.1	-8.76	24960	23.3	24.1	12.8	11.26	8PSK	1872000
27	2067.7	156.0	-8.76	24960	21.3	22.1	12.8	9.31	QPSK	561600
27	2256.4	156.8	-8.76	24960	20.6	21.3	12.8	8.55	QPSK	561600
Total (bps)										24715200
Total (Mbps)										24.7

(c)

Duration (sec)	Ranges (km)	Total losses (dB)	G/T (dB/k)	Occ BW	C/N (dB)	Eb/No (dB)	Required Eb/No (dB)	Margin (dB)	Mod	Throughput (bps)
60	2284.4	156.9	-8.76	24960	24.4	25.2	12.8	12.42	QPSK	1248000
60	1871.1	155.2	-8.76	24960	26.2	27.0	12.8	14.16	16QAM	2496000
60	1457.6	153.0	-8.76	24960	28.3	29.1	12.8	16.33	16QAM	2496000
60	1052.9	150.2	-8.76	24960	31.2	32.0	12.8	19.15	16QAM	2496000
60	676.7	146.3	-8.76	24960	35.0	35.8	12.8	22.99	64QAM	3684000
60	418.7	142.1	-8.76	12720	42.1	42.9	12.8	30.09	256QAM	4992000
60	512.03	143.9	-8.76	12720	40.3	41.1	12.8	28.34	256QAM	4992000
60	847.5	148.3	-8.76	24960	33.0	33.8	12.8	21.04	64QAM	3684000
60	1241.6	151.6	-8.76	24960	29.7	30.5	12.8	17.72	16QAM	2496000
60	1652	154.1	-8.76	24960	27.2	28.0	12.8	15.24	16QAM	2496000
27	2067.7	156.0	-8.76	24960	25.3	26.1	12.8	13.29	16QAM	1123200
27	2256.4	156.8	-8.76	24960	24.5	25.3	12.8	12.53	16QAM	1123200
Total (bps)										33326400
Total (Mbps)										33.3

TABLE V
NUMBER OF PHOTOS PER COMMUNICATION WINDOW

Quantities	Case-1	Case-2	Case-3
Total bits in one commun. window	13603200	24715200	33326400
Total frame size (bit)	2208	2208	2208
Frame size for CubeSat data	2048	2048	2048
Number of frames in one commun. window	6161	11193	15093
Size of beacon data in one day (bit)	806406	806406	806406
Size of photo data (bit)	3686400	3686400	3686400
Number of frames for beacon data	394	394	394
Number of frames for photo data	1800	1800	1800
Available number of frames per commun. window	5767	10799	14699
Number of photos per commun. window	3	5	9

TABLE VI
NUMBER OF PHOTOS DOWNLOADED IN WHOLE MISSION

Evaluation criteria	Case-1	Case-2	Case-3
# photos per communication window	3	5	9
# windows per mission	394	394	394
# photos per CubeSat mission	1182	1970	3546
Diff. in # photos: Cases 1, 2 vs. 3	/	788	1576
Diff. in # photos: Cases 1 vs. 3	/	/	2364

[8] J. A. Downey, "Variable coding and modulation experiment using NASA's space communication and navigation testbed," National Aeronautics and Space Administration (NASA), Glenn Research Center, USA, Tech. Rep., 2016.

[9] J. Downey, D. Mortensen, M. Evans, J. Briones, and N. Tollis, "Adaptive coding and modulation experiment using NASA's space communication and navigation testbed," American Institute of Aeronautics and Astronautics (AIAA), USA, Tech. Rep. AIAA 2016-5736, 2016.

[10] Z. K. Lee-Ho, "Mission operation for the Kumu A'O CubeSat," University of Hawaii at Manoa, USA, Tech. Rep., 2003, http://www.spacegrant.hawaii.edu/reports/18_FA07/ZLeeho_FA07.pdf.