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An Optimum Space-to-Ground Communication Concept for CubeSat Platform Utilizing NASA Space Network and Near Earth Network

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ABSTRACT

National Aeronautics and Space Administration (NASA) CubeSat missions are expected to grow rapidly in the next decade. Higher data rate CubeSats are transitioning away from Amateur Radio bands to higher frequency bands. A high-level communication architecture for future space-to-ground CubeSat communication was proposed within NASA Goddard Space Flight Center. This architecture addresses CubeSat direct-to-ground communication, CubeSat to Tracking Data Relay Satellite System (TDRSS) communication, CubeSat constellation with Mothership direct-to-ground communication, and CubeSat Constellation with Mothership communication through K-Band Single Access (KSA).

A study has been performed to explore this communication architecture, through simulations, analyses, and identifying technologies, to develop the optimum communication concepts for CubeSat communications. This paper presents details of the simulation and analysis that include CubeSat swarm, daughter ship/mother ship constellation, Near Earth Network (NEN) S and X-band direct to ground link, TDRSS Multiple Access (MA) array vs Single Access mode, notional transceiver/antenna configurations, ground asset configurations and Code Division Multiple Access (CDMA) signal trades for daughter ship/mother ship CubeSat constellation inter-satellite cross link. Results of space science X-band 10 MHz maximum achievable data rate study are summarized. CubeSat NEN Ka-Band end-to-end communication analysis is provided. Current CubeSat communication technologies capabilities are presented. Compatibility test of the CubeSat transceiver through NEN and SN is discussed. Based on the analyses, signal trade studies and technology assessments, the desired CubeSat transceiver features and operation concepts for future CubeSat end-to-end communications are derived.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Near Earth Network (NEN) is comprised of stations distributed throughout the world in locations including Svalbard, Norway; Fairbanks, Alaska; Santiago, Chile; McMurdo, Antarctica; and Wallops Island, Virginia.[1]. Figure 1 is an overview of the NEN. The NEN supports spacecraft trajectories from near earth to two million kilometers.

The NASA Tracking and Data Relay Satellite (TDRS) System (TDRSS) provides continuous global communications and tracking services to low earth orbiting satellites including the International Space Station, earth observing satellite, aircraft, scientific balloons, expendable launch vehicles, and terrestrial systems. The global TDRS fleet currently consists of four first-generation, three second-generation and two third generation satellite supported by three tracking stations, two at White Sands, New Mexico, and a third on the Pacific island of Guam. The third third-generation satellites will be deployed in early of 2018. This combination of nine relay satellites and three ground stations comprise NASA's Space Network (SN) [2]. Figure 2 provides a representative overview of the NASA SN.

CubeSats and SmallSats provide a cost-effective, high return on investment for conducting science missions by using miniaturized scientific instruments and bus components. Higher data rate CubeSats are transitioning away from Amateur Radio bands to S and X-bands in the near and mid-term and Ka-band in the long term, now requiring CubeSat communication hardware standardization and compatibility with NEN and SN. Based on a high-level communication architecture for future space-to-ground CubeSat communication proposed within NASA Goddard Space Flight Center (GSFC), a study was conducted to develop communication concepts guiding the standardization of communication hardware to meet the GSFC mission needs, with the ultimate goal of increasing interoperability with NEN and SN and increasing science data return.

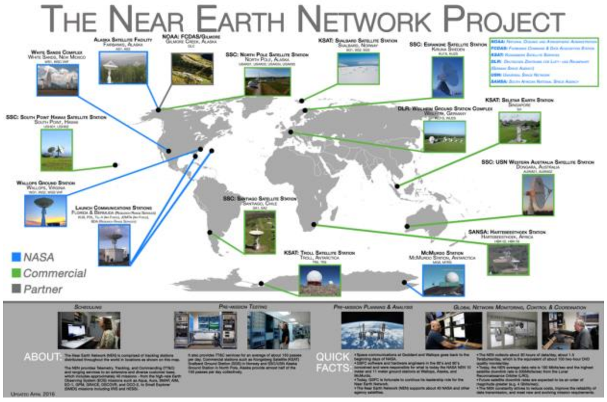


Figure 1: NASA NEN Overview

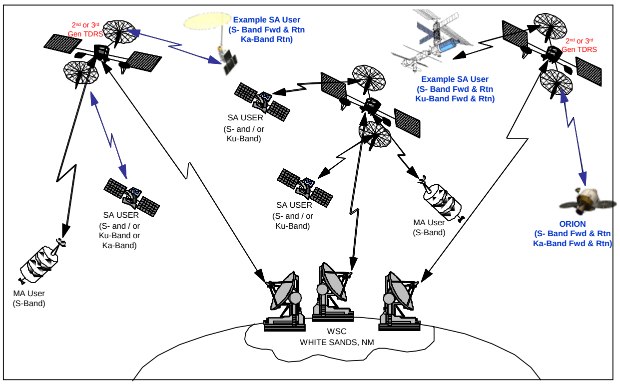


Figure 2: NASA SN Network Overview

This paper describes the study objectives and NASA communication architecture for future CubeSat missions. Results of CubeSat Near Earth Network (NEN) and Space Network (SN) support analysis are presented. CubeSat constellation concept and inter satellite link Coded Division Multiple Access (CDMA) signal model and trades study are discussed. A simulation model with power and bandwidth efficient signal schemes to study CubeSat maximum achievable data rate for NEN space science X-band downlink 10 MHz channel is presented and the results are discussed. Results of NEN CubeSat Ka-band end-to-end communication analysis using portable antenna system are summarized. CubeSat radio and antenna technologies TRL assessment summary is presented. Compatibility test of the CubeSat transceiver through NEN and SN is discussed. Operation concepts for CubeSat end-to-end communication, based on results of the study, are proposed. Finally, NEN Lunar CubeSat support concept and the NASA NEN/SN CubeSat support strategy are discussed.

STUDY OBJECTIVES

1. Perform study to develop optimum communication concepts for CubeSat platform utilizing NASA SN and NEN

2. Perform detailed analyses and simulations of the proposed communication architecture configurations. This includes CubeSat swarm, daughter ship/mother ship constellation, NEN S- and X-band direct-to-ground link, TDRSS MA array vs Single Access mode, notional transceiver/antenna configurations, ground asset configurations, signal trades, space science X-band 10 MHz maximum achievable data rates

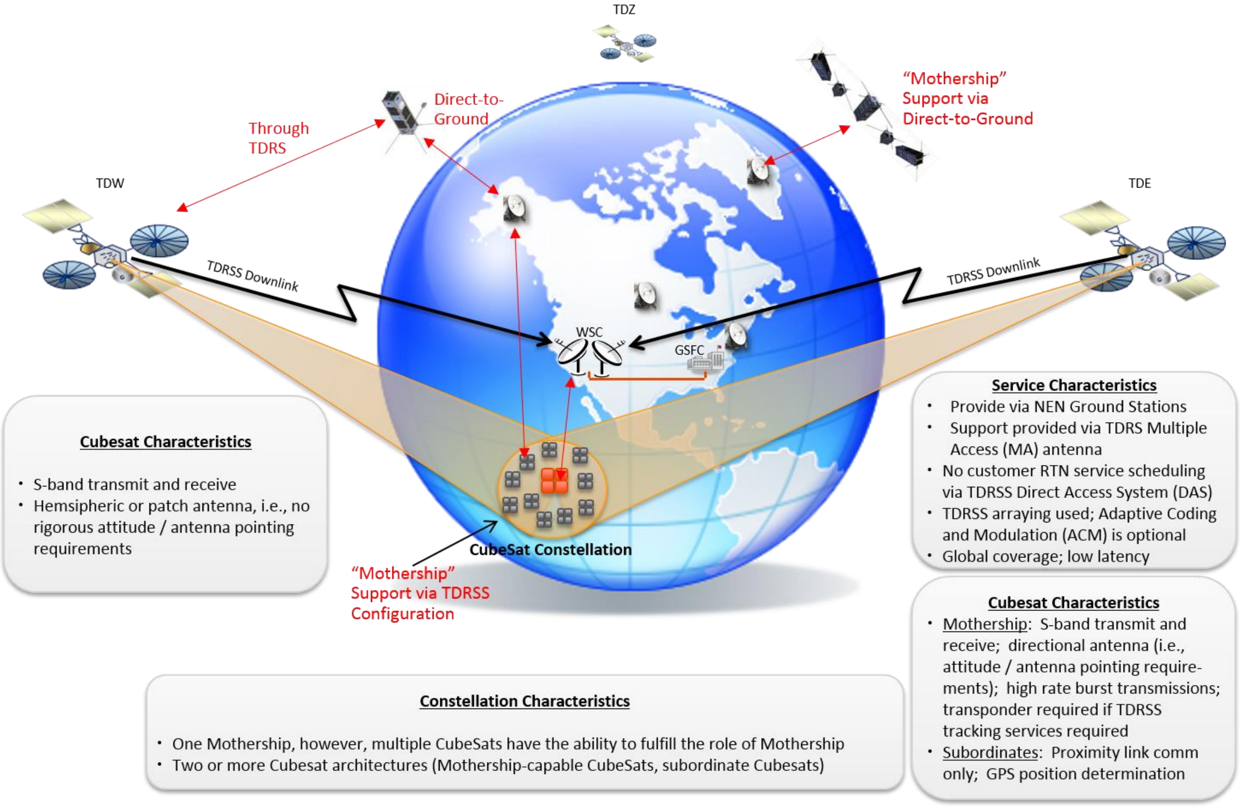
3. Explore CubeSat current technologies capabilities

4. Develop concepts of operations, and communication requirements for NASA's future CubeSat/SmallSat end-to-end communication

5. Provide innovation concepts to meet future CubeSat/SmallSat communication needs.

NASA FUTURE CUBESAT AND SMALLSAT COMMUNICATION ARCHITECTURE AND CONFIGURATION

The proposed NASA future CubeSat/SmallSat communication configurations are depicted in Figure 3: CubeSat to NEN direct-to-ground communication, CubeSat to TDRSS MA array communication, CubeSat constellation with mother ship communication through NEN direct-to-ground communication, and CubeSat Constellation with mother ship communication through TDRSS MA array or K-Band Single Access (KSA)/S-Band Single Access (SSA).



Cubesat Characteristics

- S-band transmit and receive
- Hemispheric or patch antenna, i.e., no rigorous attitude / antenna pointing requirements

Service Characteristics

- Provide via NEN Ground Stations
- Support provided via TDRS Multiple Access (MA) antenna
- No customer RTN service scheduling via TDRSS Direct Access System (DAS)
- TDRSS arraying used; Adaptive Coding and Modulation (ACM) is optional
- Global coverage; low latency

Cubesat Characteristics

- Mothership: S-band transmit and receive; directional antenna (i.e., attitude / antenna pointing requirements); high rate burst transmissions; transponder required if TDRSS tracking services required
- Subordinates: Proximity link comm only; GPS position determination

Constellation Characteristics

- One Mothership, however, multiple CubeSats have the ability to fulfill the role of Mothership
- Two or more Cubesat architectures (Mothership-capable CubeSats, subordinate Cubesats)

Figure 3: SN and NEN Supports both Single CubeSats and CubeSat Constellations

NEAR EARTH NETWORK (NEN) CUBESAT SUPPORT ANALYSIS

Link analysis/coverage analysis had been performed showing that Cubesat/Smallsat mission communication requirements including frequencies and data rates can be met by utilizing NEN S and X-band support [3].

Table 1: NEN Support Link Analysis

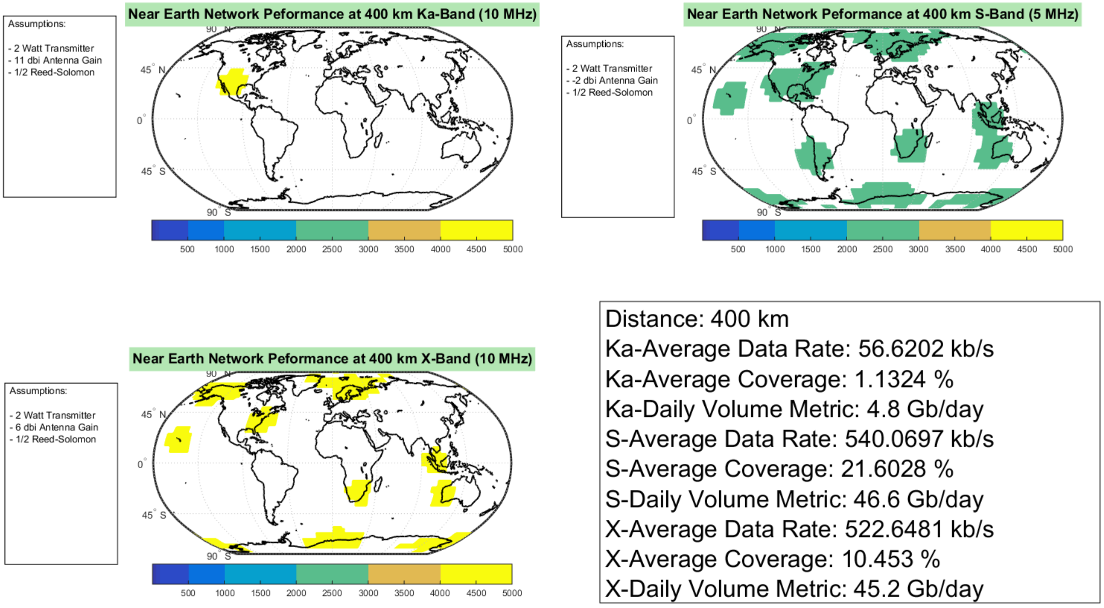
Links	Data Rate	Mod & Coding	CubeSat EIRP	Link Margin
S-band Downlink	2 kbps	BPSK, ½ conv + RS	-1 dBw	40.1 dB
S-band Downlink	4 kbps	BPSK, ½ conv	-1 dBW	36.5 dB
S-band Downlink	256 kbps	BPSK, ½ conv	-1 dBW	18.45 dB
S-band Downlink	513.7 kbps	BPSK, RS	-1 dBW	14.4 dB
X-band Downlink	13.1 Mbps	QPSK, 7/8 LDPC	5 dBW	10.3 dB
X-band Downlink	130 Mbps	QPSK, ½ conv + RS	5 dBW	3.2 dB

11.3 m at AS1, CubeSat PA = 1 W, 0 dBi Antenna Gain (S-band), Antenna Gain = 5 dBi (X-band). S/C at 745 km altitude

The required Cubesat EIRP can be met with practical spacecraft (S/C) power amplifier (PA) 1 W/2 W and patch antenna zero dBi gain (S-band) earth coverage antenna 6 dBi gain (X-band) with plenty of link margin. Table 1 is summary of the link analysis for representative date rate, required EIRP, modulation and coding schemes, ground station parameters and link margin.

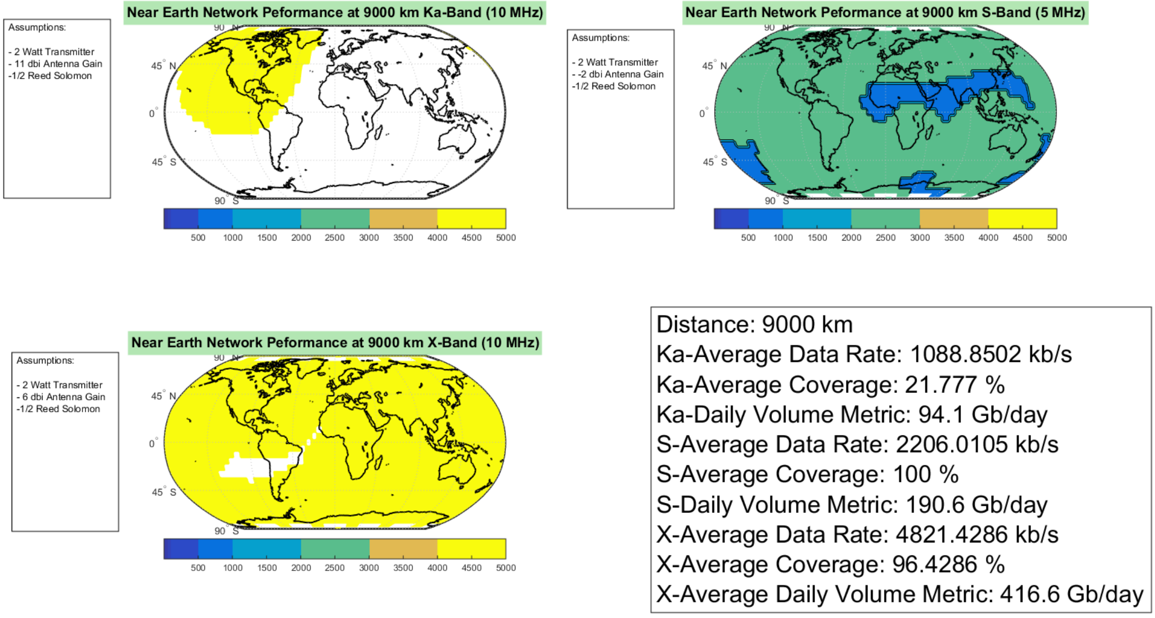
A 3-D Volumetric Analysis has been performed using Simulation Tool Kit (STK). Performance shells were calculated at different altitude levels in MATLAB to determine expected Coverage/Performance metrics. Figures 4-6 show NEN performance as spacecraft go farther and farther from the earth. Each figure contains metrics associated with each altitude. Average Data Rate is defined as the weighted average of data rates over the earth coverage. Earth Coverage is defined as the percentage of Earth that is in view of the Near Earth Network, and the Daily Volume Metric is the percent coverage multiplied by the average data rate. Different frequencies have different spacecraft assumptions, for instance the X-band system is assumed to have 6 dB more antenna gain. And the color bars are represented in kbps.

At 400 km, all spacecraft at their bandwidth limitation have extra link margin and full earth coverage has not been achieved at this attitude. At 9000 km altitude CubeSats start seeing their first performance degradation in S-Band but full earth coverage is achieved. At 400000 km, X-band data rate can achieve 10 kbps for the majority of the earth's coverage but S-Band data Rates are limited to 3 kbps on average.



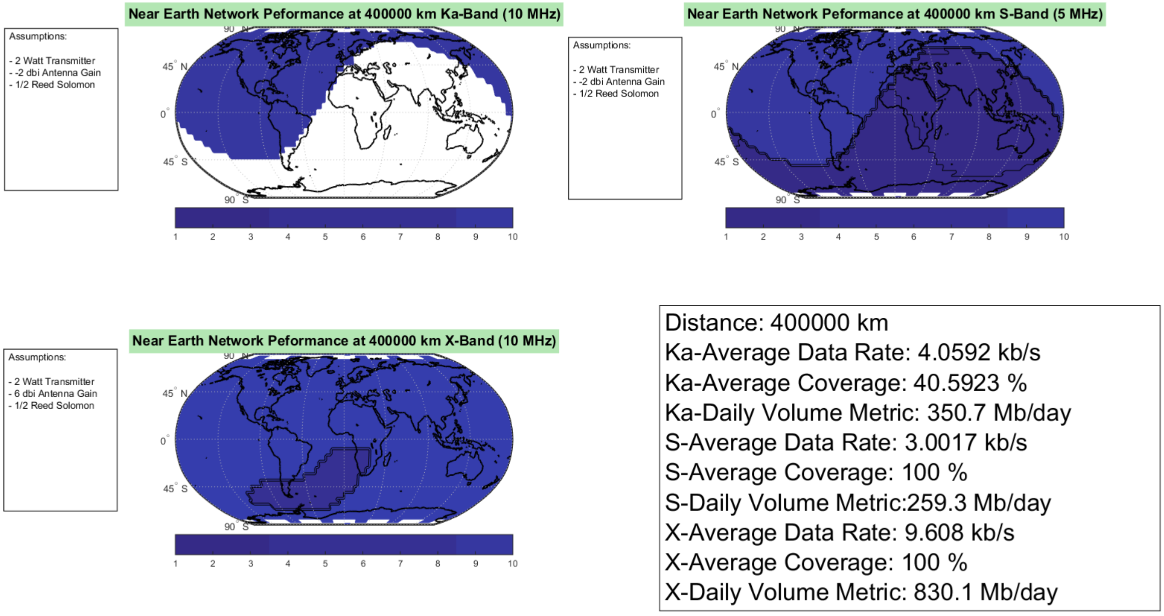
Distance: 400 km
Ka-Average Data Rate: 56.6202 kb/s
Ka-Average Coverage: 1.1324 %
Ka-Daily Volume Metric: 4.8 Gb/day
S-Average Data Rate: 540.0697 kb/s
S-Average Coverage: 21.6028 %
S-Daily Volume Metric: 46.6 Gb/day
X-Average Data Rate: 522.6481 kb/s
X-Average Coverage: 10.453 %
X-Daily Volume Metric: 45.2 Gb/day

Figure 4: Performance Results at 400 km altitude.



Distance: 9000 km
Ka-Average Data Rate: 1088.8502 kb/s
Ka-Average Coverage: 21.777 %
Ka-Daily Volume Metric: 94.1 Gb/day
S-Average Data Rate: 2206.0105 kb/s
S-Average Coverage: 100 %
S-Daily Volume Metric: 190.6 Gb/day
X-Average Data Rate: 4821.4286 kb/s
X-Average Coverage: 96.4286 %
X-Average Daily Volume Metric: 416.6 Gb/day

Figure 5: Performance Results at 9000 km altitude.



Distance: 400000 km
Ka-Average Data Rate: 4.0592 kb/s
Ka-Average Coverage: 40.5923 %
Ka-Daily Volume Metric: 350.7 Mb/day
S-Average Data Rate: 3.0017 kb/s
S-Average Coverage: 100 %
S-Daily Volume Metric:259.3 Mb/day
X-Average Data Rate: 9.608 kb/s
X-Average Coverage: 100 %
X-Daily Volume Metric: 830.1 Mb/day

Figure 6: Performance Results at 400000 km (Lunar) altitude.

SPACE NETWORK (SN) CUBESAT SUPPORT ANALYSIS

CubeSat TDRSS support will be limited by lower data rate due to power constraint on the spacecraft and the distance between the spacecraft and the satellite relay. TDRSS can provide global coverage to CubeSats with low latency, compared to limited contact time with just ground stations. More coverage time via TDRSS mitigates the power constraint by using lower data rates to deliver more data than brief, intermittent ground station contacts. It is ideal for emergency support. A CubeSat could send status alerts instantly without waiting until a ground station is in view. Link analysis indicates that TDRSS legacy Multiple Access (MA) is able to support CubeSat data rate near 1 kbps (859 bps) with practical S/C power amplifier 2 W and a zero dBi user antenna gain. With TDRSS HIJ S-band MA (higher TDRS EIRP), the support data rate is little higher to 1.3 kbps rate (same S/C EIRP) [4].

TDRSS Multiple Access (MA) arraying with at least two TDRS in view is able to support an even higher data rate (15 kbps with a 3W PA and 0 dBi antenna gain, 15 kbps with a 3W PA and 0 dBi antenna gain, rate ½ LDPC coding, user post-PA cable loss of 0.8 dB and implementation loss of 1.5 dB). The arraying capability has been demonstrated multiple times. It was demonstrated with both Swift and Fermi missions. The SN would support arraying for CubeSat missions for any mission deemed important enough to NASA. A CubeSat constellation demonstration mission using MA, consuming TDRS Unused Time, and scheduled through the Demand Access System at White Sands would be endorsed by the SN.

In order for CubeSats to use TDRSS S-band Single Access (SSA) and Ka-Band Single Access (KaSA) support, they need a deployable high gain antenna on board to produce positive link margin. An EIRP of 13 dB is required to produce a 1 dB link margin for SSA return 100 kbps data rate. For KaSA support, a data rate of 39.5 Mbps is achieved with a 2 W PA and a 36 dBi deployable antenna with Offset Quadrature Phase Shift Keying (OQPSK) and rate 1/2 Low Density Parity Check (LDPC) coding. The data rates will be reduced to 19.45 Mbps if rate 1/2 convolutional code is used. [4]

Figure 7 shows that TDRSS will provide 100% coverage for CubeSat in a LEO at an altitude of 500 km.

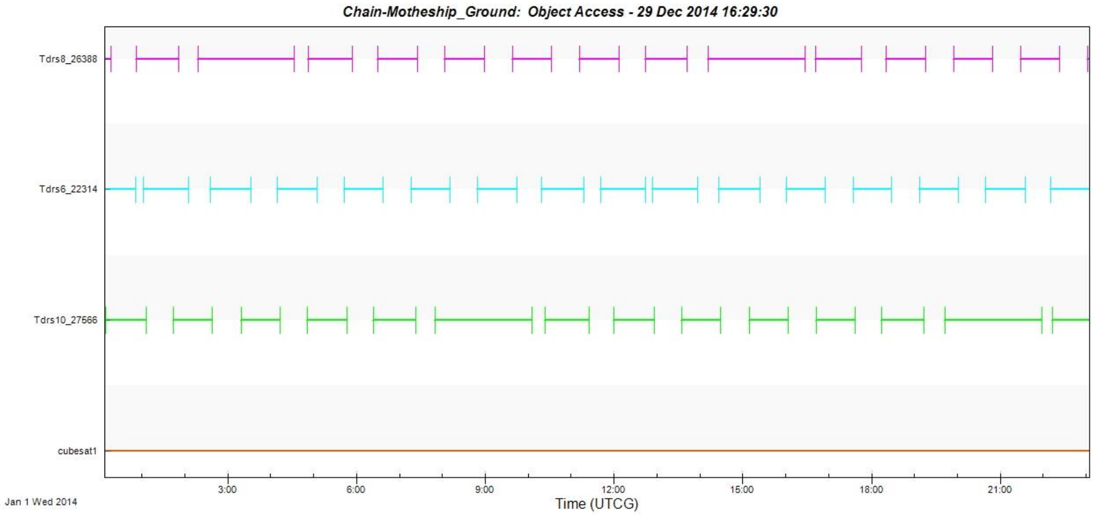


Figure 7: TDRS Daily Coverage for CubeSat at 500 km Altitude

CUBESAT CONSTELLATION NEN/SN SUPPORT

CubeSat constellations are designed to optimize coverage over specific areas or improve global revisit times to fulfill the mission purpose. There is growing interest among the NASA science community in using constellation of CubeSats to enhance observations for earth and space science. As shown in Figure 3 of NASA future CubeSat/SmallSat communication configurations, the CubeSat constellation communication concepts with respect to NEN/SN contains several scenarios. This includes CubeSat swarms, daughter ship/mother ship constellations, NEN S- and X-band direct-to-ground links, Tracking and Data Relay Satellite System (TDRSS) Multiple Access (MA) array and Single Access modes.

A CubeSat constellation may involve numerous CubeSats in the constellation, (e.g., tens or hundreds). Each CubeSat is typically identical from a communication perspective. One CubeSat may be mother ship-capable while the others may be subordinate (i.e. daughter ships), however, multiple CubeSats may have the ability to fulfill the role of a mother ship.

The mother ship may be a store-forward relay which is capable of transmit/receive between the subordinate CubeSats and may downlink the science data to the ground either through a NEN direct to ground link at X-band or through a TDRSS Ka-band Single Access (KaSA) service. Patch antennas may be used between the mother ship and the subordinate CubeSats for the inter-satellite communication link to provide the required omni-coverage using an accurate attitude pointing system for each daughter ship. Earth coverage antennas in X-band with uniform gain may be used for communication between the mother ship and NEN ground stations for high data rate downlink.

Given the limited CubeSat transmit power, communication with TDRSS KaSA mode requires a steering antenna or inflatable/phased array antenna on board the mother ship for a high data rate downlink. In case of emergency or other reasons, the CubeSat communication may take place directly through TDRSS MA array mode or NEN direct to ground station mode.

CUBESAT CONSTELLATION INTER SATELLITE LINK CODED DIVISION MULTIPLE ACCESS (CDMA) SIGNAL SIMULATION MODEL AND TRADES STUDY

A CDMA signal simulation model (in spread sheet format) was developed as a tool to support the analysis and trades study of CubeSat constellation inter-satellite link signal/orbit design optimization. The study was intended to solve for the most appropriate CDMA signal characteristics/design and CubeSat orbit for mother/daughter constellation inter-satellite link communications that would be able to downlink an adequate daily data volume to the ground. The mother CubeSat will be a store-forward relay to downlink the science data to the ground either through NEN direct to ground link at X-band or through TDRSS K-band single access (KSA).

This model takes into account communication parameters including modulation and coding type, pseudorandom noise (PN) chip rate, carrier frequency at S-band, performance requirements (theoretical required Eb/No, implementation loss, link margin), CubeSat daughter and mother ship transmitter power, cable loss, antenna gain, mother ship and G/T. The model is able to calculate total daily volume based on maximum data rate determination. The study assumes practical Cubesat communication parameters such as 2 W PA, zero dBi antenna gain, rate ½ and rate 7/8 LDPC code, 3Mcps PN chip rate, and mother ship G/T: -27 dB/K. All Cubesats use GPS for position identification, (i.e., the mother-daughter cross-links are not required to support tracking services). The study assumes a mother ship to daughter ship forward link that is used to command the daughter ship to downlink science data to the mother ship and to provide mother ship position information to the daughter ship. The benefit of CDMA is that you do not need to perform frequency management and every transmitter / receiver is manufactured exactly the same.

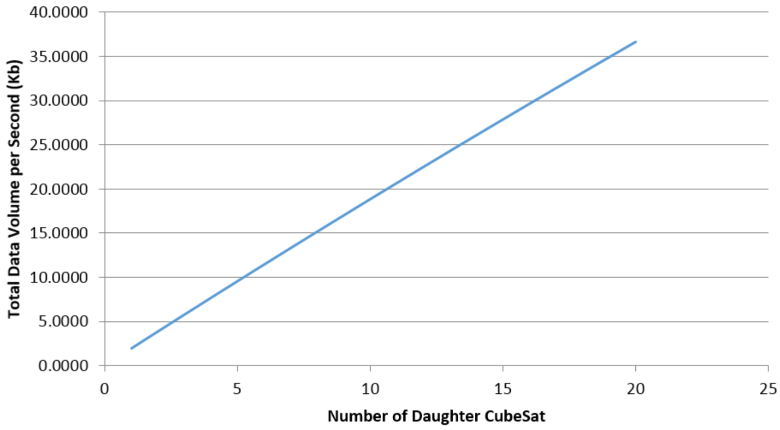
Table 2 illustrates the total daily volume calculation using the spread sheet simulation model with various combinations of CDMA signal parameters and the mother-daughter ship slant range is 1000 km. The calculation takes into account the effect of mutual interference with respect to the number of daughter CubeSats on maximum achievable data rate and total daily volume. As indicated, the achievable CubeSat data rate is decreased from 3.8607 kbps to 3.6613 kbps if the number of CubeSat in the constellation is increased from 2 to 20.

Table 2: CubeSat Inter-Satellite Link CDMA Model Total Daily Volume Calculation Example

Modulation	QPSK
Carrier frequency (MHz)	2250
Chip rate (Mcps)	3
Eb/N0 for 10E-5 BER (dB)	3.85
Imp. Loss (dB)	2.4
margin (dB)	2
Eb/No required (dB)	8.25
Coding rate	0.875
Per channel Es/No required (dB)	7.67008053
Duty cycle	0.5

Daugher ship transmiting power (dBW)	3.010299957
Daughter ship cable loss (dB)	1
Daughter ship antenna gain (dBi)	0
Daughter ship transmitting EIRP (dBW)	2.010299957
Mother-daughter ship range (Km)	1000
Path loss (dB)	159.4936504
Power received (dBW)	-157.4833504
Boltzmann's constant (dBW/Hz-K)	-228.6
Mother ship G/T (dB/K)	-27
C/No(dB-Hz)	44.11664959
Per channel C/No(dB-Hz)	41.10634964

No. of daugher cubesat	MAI (No+Io)/ No in dB	Max. achieveable data rate (Kbps)	Total data volumn per second (Kb)
1	0.0000	3.8607	1.9303
2	0.0124	3.8497	3.8497
3	0.0248	3.8387	5.7580
4	0.0372	3.8278	7.6555
5	0.0495	3.8169	9.5423
6	0.0618	3.8061	11.4184
7	0.0741	3.7954	13.2839
8	0.0863	3.7847	15.1389
9	0.0985	3.7741	16.9836
10	0.1106	3.7636	18.8179
11	0.1228	3.7531	20.6420
12	0.1348	3.7427	22.4560
13	0.1469	3.7323	24.2599
14	0.1589	3.7220	26.0538
15	0.1709	3.7117	27.8378
16	0.1829	3.7015	29.6121
17	0.1948	3.6914	31.3766
18	0.2067	3.6813	33.1314
19	0.2185	3.6712	34.8767
20	0.2304	3.6613	36.6125



CDMA Trade Studies for Formation Flying Scenarios

In these scenarios, the study assumes the constellation contains 20 daughters with 1 mother CubeSat. The CubeSat daughter and mother ships are in formation flying. CubeSats are deployed out of the launch vehicle on a strict timeline and all possess the ability to station keep and maintain a formation. It is assumed that the slant range between daughter and mother ships is 100 km. The daughter ship CubeSat PA is 2W with a zero dBi antenna gain. Mother ship CubeSat G/T is -27 dB/K. Carrier frequency is 2.25 GHz at S-band. The daughter ship communication duty cycle is 50%. Results of the study for total daily data volume with the slant range of 100 km in the daughter/mother ship constellation orbit are shown in Table 3.

With the CubeSat communication parameters fixed, the maximum data rates are determined as a function of slant range. The mutual interference effect is taken into account for the data rate with 20 daughter ship CubeSats. Based on the maximum achievable data rates, the total daily data volumes are 34.3 Gbits, 21.1 Gbits, 82.1 Gbits, 50.6 Gbits accordingly.

Table 3. Data Volume Versus Coding

Parameter	Value			
Slant range (Km)	100			
Modulation	QPSK			
Chip rate (Mcps)	1		3	
Coding	1/2 LDPC	7/8 LDPC	1/2 LDPC	7/8 LDPC
Theoretical Eb/No for 10-5 BER (dB-Hz)	1.75	3.85	1.75	3.85
Imp. Loss (dB)	1.8	1.8	2.0	2.0
Margin (dB)	2.0	2.0	2.0	2.0
Max. achievable dara rate with 20 simultaneous daughter ships (Kbps)	39.7	24.5	95.0	58.6
Total data volume per second (Kb)	397.0	245.0	950.0	586.0
Total daily data volume (Gb)	34.3	21.1	82.1	50.6

CDMA Trade Studies for Unsynchronized Flying Scenarios

In these scenarios, the study assumes the constellation contains 20 daughter ships with 1 mother ship CubeSat. CubeSats are deployed out of the launch vehicle on no strict timeline and with no ability to station keep after being deployed. A simulated CubeSat orbit for 14 days was used to support the analysis. The orbits are based upon all Cubesats are being in typical Cubesat orbits, but are unsynchronized with each other. Results of the study/analysis are shown in Tables 4 and 5.

Table 4. Data Volume Versus Slant Range for 1/2 LDPC

Max-Supported Mother-to-Daughter Slant Range (km)	**Probability That Daughter CubeSat Is Within This Slant Range**	**Maximum Number of Daughters Within This Slant Range**	**Maximum Achievable Data Rate (per Daughter, Kbps)**		**Maximum Achievable Daily Data Volume (per Daughter, Mb)**	
			1 Daughter	Max # of Daughters	1 Daughter	Max # of Daughters
				All effectively at Max-Supported Slant Range via Power Control		All effectively at Max-Supported Slant Range via Power Control
250	0~0.13%	1	102.514	102.514	0~11.51	0~11.51
1000	0.26~3.98%	3	6.407	6.371	1.44~22.03	1.43~21.91
3000	2.30~13.23 %	6	0.712	0.711	1.41~8.14	1.41~8.13
5000	6.83~28.37 %	10	0.256	0.256	1.51~6.27	1.51~6.27

Table 5. Data Volume Versus Slant Range for 7/8 LDPC

Max-Supported Mother-to-Daughter Slant Range (km)	**Probability That Daughter CubeSat Is Within This Slant Range**	**Maximum Number of Daughters Within This Slant Range**	**Maximum Achievable Data Rate (per Daughter, Kbps)**		**Maximum Achievable Daily Data Volume (per Daughter, Mb)**	
			1 Daughter	Max # of Daughters	1 Daughter	Max # of Daughters
				All effectively at Max-Supported Slant Range via Power Control		All effectively at Max-Supported Slant Range via Power Control
250	0~0.13%	1	61.771	61.771	0~6.94	0~6.94
1000	0.26~3.98%	3	3.861	3.839	0.87~13.28	0.86~13.20
3000	2.30~13.23%	6	0.429	0.428	0.85~4.90	0.85~4.89
5000	6.83~28.37%	10	0.154	0.154	0.91~3.77	0.91~3.77

Table 4 is based on communication of SQPSK Rate 1/2 LDPC, 3Mcps, 2W flight PA, daughter ship zero dBi antenna gain, mother ship G/T: -27 dB/K, link margin 2 dB, with daughter ships keeping 100% communication with the mother ship when they are within the maximum supported slant range. With these parameters fixed, data rates are determined as a function of slant range. In the case of more than one daughter ship within the slant range, data rate will be slightly degraded due to mutual interference effect (see columns four and five of Table 4).

Table 5 is based on communication of SQPSK Rate 7/8 LDPC. The other parameters are the same as in Table 4. As shown in Tables 4 and 5, 1/2 LDPC is better than 7/8 LDPC for data rate, and total daily data volume. It is due to the coding gain of 1/2 LDPC being better than 7/8 LDPC. If there is only one daughter, the maximum achievable data rate in columns four and five are the same. If there is more than one daughter, the maximum achievable data rate is reduced slightly due to mutual interference. The same is true for the maximum achievable daily data volume.

With the CDMA signal design, as shown in Tables 4 and 5, the constellation mother/daughter ship architecture is able to produce an adequate daily data volume if the daughter and mother ship CubeSats are in a coordinated orbit (for instance, formation flying). The CDMA signal parameters can be traded to produce an optimum daily data volume.

If the mother/daughter ship CubeSats are in un-synchronization orbit, in order to downlink a meaningful/adequate daily volume of science data, the use of a mother ship CubeSat as a store-forward relay requires intelligent protocols capable of performing efficient management and operation control of signal flow for the inter-satellite links. Cognitive radio/ad-hoc networking is a potential candidate technique for providing the functions necessary for an autonomous CubeSat inter-satellite communication network management system.

Cognitive radios with intelligent protocols offer a potential solution for managing NEN direct to ground communication support of CubeSats constellations in un-synchronized orbits without a mother/daughter ship architecture. This could lessen the load on scheduling system personnel.

As shown in Tables 4 and5, the maximum achievable date rates are less than 7 kbps for the mother-to-daughter ship slant range 1000 km and larger. The smaller data rates are due to the relative large increase in free space loss in such ranges. Switching from S-band to X-band frequency with a more powerful antenna will enable much higher data rate for the inter-satellite link. Micro-strip array X-band antenna with a gain of at least 11 dBi is available in the market. The size is 86x86mm that was designed to fit on a 1U end-face of a 3U CubeSat.

CUBESAT SPACE SCIENCE NEN X-BAND 10 MHZ CHANNEL DOWNLINK ACHIEVABLE DATA RATE

Space science missions are granted 8450-8500 of the X-band spectrum with a limitation of only 10 MHz of bandwidth per mission. A study has been conducted to determine the maximum achievable data rate in the NEN X-band 10 MHz bandwidth channel downlink without violating power flux density limits [5]. This study applies to both CubeSat and non-CubeSat traditional missions.

Objectives of the study

1. Identify modulation with rate 7/8 LDPC coding which maximizes the data rate through the CubeSat NEN X-band 10 MHz downlink

2. Provide a recommendation to identifying which modulation techniques with rate 7/8 LDPC coding would be most appropriate to support CubeSat NEN X-band 10 MHz downlink

Approach Overview

1. Developed 16APSK, 16QAM, and 32APSK rate 7/8 LDPC coded CubeSat NEN end-to-end MATLAB®/SIMLINK simulation models

2. Reasonable amount of CubeSat transmitter distortions and ground terminal distortions were assumed

3. Simulations performed to determine the (Spell out) BER performance of the these modulation schemes with rate 7/8 LDPC and distortion scenarios considered in this study

4. Compute link margin using link budget analysis

MATLAB®/SIMLINK End-to-End Model Example

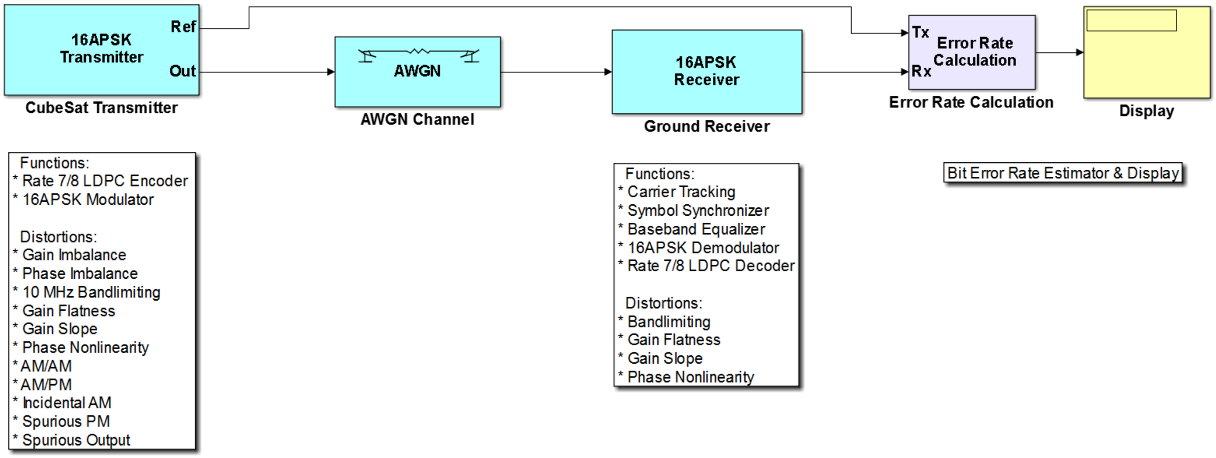


Figure 8: MATLAB®/SIMLINK NEN X-band 10 MHz NEN End-to-End Simulation Model

MATLAB®/SIMLINK Transmitter/Receiver Model Example

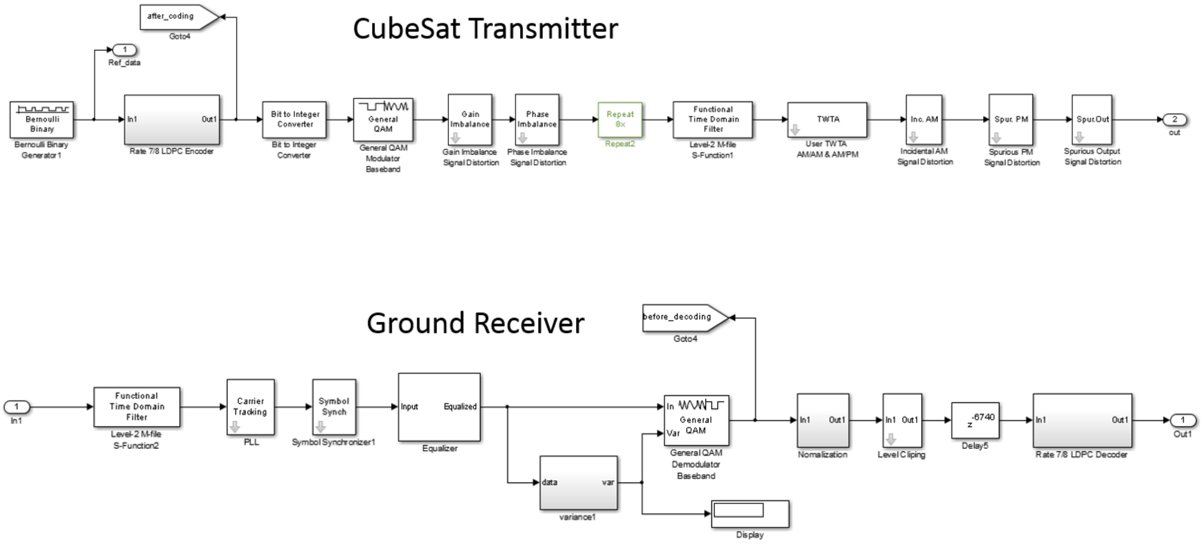


Figure 9: MATLAB®/SIMLINK Transmitter/Receiver Model Example

CubeSat Flight System Parameters: CubeSat antenna gain in direction of NEN station: 6 dBi; CubeSat transmitter power: 2 W to 5 W; CubeSat at an altitude of: 500 km; Minimum elevation angle: 10°; CubeSat transmitter filtering with two-sided bandwidth of 10 MHz.

NEN Ground Terminal Equipment: Output BER of 10e-5 required for support by Ground Terminal equipment; Integrate and dump detection is used; Adaptive baseband equalization is used; Physical layer code frame synchronization is ideal.

Results Summary

A summary of the study results is shown in Table 6.

Table 6: Summary of Study Results

Modulation	Coding	Max Data Rate	Implementation loss at 10-5 BER	Comment
OQPSK	7/8 LDPC	16 Mbps	3.6 dB	There is significant positive link margin assuming a CubeSat effective isotropic radiated power (EIRP) with 8.0 dBW (2 Watt TX Power).
8PSK	7/8 LDPC	23.6 Mbps	4.1 dB	Same as in OQPSK
16 APSK	7/8 LDPC	28 Mbps	> 6 dB	For the 6 dB implementation loss case, it was assumed that the CubeSat transmitter distortions are the same as defined in the Space Network Users Guide (SNUG). S-band Single Access Return (SSAR) user distortions were used except with a lower Power Amplifier (PA) nonlinearity. For the 5 dB case, it was assumed the CubeSat transmitter had less distortions than the SNUG defined SSAR user distortions amount and lower PA nonlinearity
			~ 5 dB	
32 APSK	7/8 LDPC	30 Mbps	>> 6dB	32 APSK should not be considered because it has minimum benefits on data rate.
			~ 5 dB	
16 QAM	7/8 LDPC	28 Mbps	> 6 dB	Considering 16 APSK can achieve the same data rate with less stringent constraints, 16 QAM should not be considered.
			~ 5 dB	

BER Simulation Results

BER Simulation Results for 16 APSK, 16 QAM and 32 APSK are shown in Figures 10, 11 & 12.

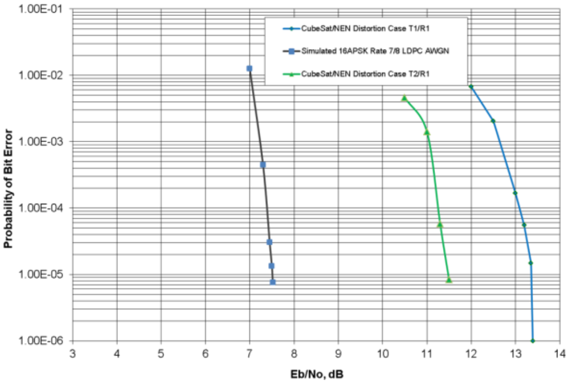


Figure 10: BER Results for 16 APSK

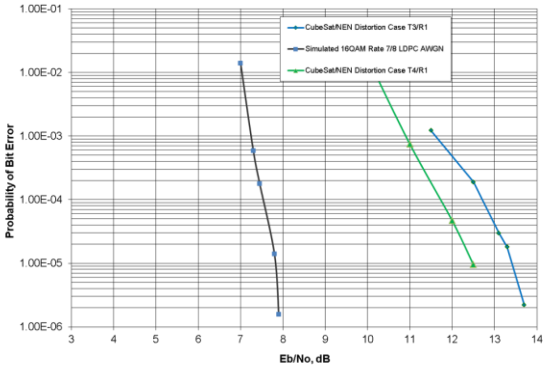


Figure 11: BER Results for 16 QAM

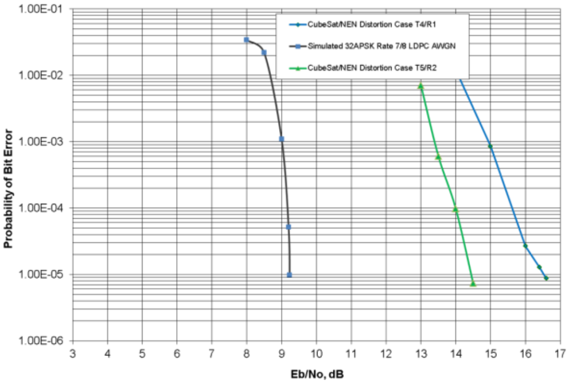


Figure 12: BER Results for 32 APSK

Conclusions and Recommendations

1. High order modulation schemes are susceptible to transmitter linear distortions and very susceptible to nonlinearity
2. CubeSat transmitter must have stringent distortion constraints (especially the nonlinearity constraint) in order to use high order modulation schemes
3. Among high order modulation schemes evaluated in this study, 16APSK is feasible since it only requires CubeSat to have a quasi-linear power amplifier, which can be done via pre-distortion compensation
4. 16QAM requires very stringent constraints on CubeSat transmitter in order to close the link with reasonable amount of link margin. Considering 16APSK can achieve the same data rate with less stringent constraints, 16QAM should not be considered
5. 32APSK should not be considered since: it has minimum benefits on data rate; it does not close the link even with very stringent constraints on CubeSat transmitter; it barely closes the link if constraints on ground terminal can be more stringent as well, however this is not realistic.

Power and Bandwidth Efficient Signal Techniques for Earth Science CubeSat High Data Rate

Due to the limited power and mass for CubeSat spacecraft, power and bandwidth efficient signal techniques such as Low-density parity-check code (LDPC) are recommended for use to achieve CubeSat high data rate requirements. As NASA earth science CubeSat mission channel bandwidth allocation at X-band is 375 MHz, high coding gain rate ½ LDPC code is preferred over the low overhead rate 7/8 LDPC code for CubeSat high data rate missions which are in the order of no more than 100 to 200 Mbps. Bandwidth is not really a concern for a majority of earth science CubeSat missions at X-band. Maximizing the efficiency of RF power is the key to achieve higher data rate. Bandwidth is an issue due to interference. Higher order modulations (8 and 16 at least) and high rate coding (4/5, 7/8, etc.) could allow more missions to co-exist without overlap to increase usage of polar regions.

Rate ½ LDPC code produces a 2.5 dB coding gain over conventional rate ½ convolutional code while rate 7/8 LDPC coding gain is only 0.5 dB better. High order modulation like 8 Phase Shift Keying (PSK) is not really necessary to be used for CubeSat missions in the X-band 375 MHz channel.

The channel bandwidth allocation for NASA CubeSat missions at S-band is only 5 Mhz. High rate LDPC code with low overhead to increase bandwidth efficiency is recommended for CubeSat NEN communication links. High order modulations like 8 PSK will be considered to increase the CubeSat data rate in the S-band 5 MHz channel. A study on the use of power and bandwidth efficient modulation and coding schemes for NEN CubeSat communication links at S and X-band for increased data rate and spectral efficiency has been conducted. CCSDS and DVB-S2 signal schemes including the LDPC family were considered in the study. Based on recommendation of the study, the Cortex receivers at NEN station may be enhanced to support future CubeSat high data rate missions.

CUBESAT KA-BAND END-TO-END COMMUNICATION ANALYSIS

A study was performed to evaluate the feasibility of Ka-band communication support for CubeSat/SmallSat science data downlink [6]. This study included link analysis to determine the achievable data rate, based on a COTS Ka-band flight hardware, a NASA Ames Miniature Ka-band transmitter Canopus Systems/CKAT-10 and a portable ground 1.2m/2.4 Ka-band antenna G/T, as well as the to-be-upgraded NEN ground stations G/T at White Sands and Alaska at Ka-band.

COTS Ka-Band Flight Hardware and Portable 1.2m/2.4m Antenna

Examples of COTS Ka-band flight transceivers and portable antennas parameters supporting NASA Ka-band frequencies are shown in Tables 7 and 8. It also includes assumptions used in calculating the CubeSat link budgets.

Table 7: COTS Ka-Band Flight System Parameters

Ka-band Downlink Parameters
• S/C Altitude: 625 km and 600 km
• Atmospheric and Rain Attenuation: based on ITU Recommendation ITU-R P.618-10 (rain model) and ITU-R P.676-8 (gas model)
• Rain Availability: 95% and 99% (Ka-band)
• Frequency: 26000 MHz
• Transmit Power: 2 Watts
• Passive Loss: 1 dB
• Earth Coverage Antenna Gain: 4 dBi
• Polarization: RHCP
• Polarization Loss: 0.1 dB
• Modulation: OQPSK
• Data Format: NRZ-L
• Telemetry Coding: Rate 1/2 LDPC
• Required Eb/No: 2.29 dB (OQPSK at BER=10^{-9}@ Rate 1/2 LDPC Decoder)

Table 8: Portable 1.2m/2.4m Antenna Parameters

Portable 1.2-Meter at Fairbanks, Alaska Ground Station	**Portable 2.4-Meter at Fairbanks, Alaska Ground Station**
• Latitude: 64.8586° N	• Latitude: 64.8586° N
• Longitude: 147.8550° W	• Longitude: 147.8550° W
• Minimum elevation: 10°	• Minimum elevation: 10°
• Ka-band Received Antenna Gain: 46.5 dBi (with 42% EFF)	• Ka-band Received Antenna Gain: 51.7 dBi (with 35% EFF)
• System Temperature: 138 °K (clear sky; reference at antenna port)	• System Temperature: 129 °K (clear sky; reference at antenna port)
• Ka-band Feed Loss: 0.5 dB	• Ka-band Feed Loss: 0.5 dB
• Ka-band T_{LNA} : 60 °K	• Ka-band T_{LNA} : 60 °K
• Antenna Noise: 90 °K (clear sky and 10º elevation angle)	• Antenna Noise: 89 °K (clear sky and 10º elevation angle)
• Ka-band G/T: 23.7 dB/K (clear sky and 10º elevation angle)	• Ka-band G/T: 28.88 dB/K (clear sky and 10º elevation angle)
• Ka-band Implementation Loss: 2.4 dB (OQPSK)	• Ka-band Implementation Loss: 2.4 dB (OQPSK)

Canopus Systems/NASA Ames Miniature Ka-band Transmitter CKAT-10

The parameters used in performing link analysis based on the Canopus System are given in Table 9. Figure 11 illustrates the Canopus system.

Table 9: Canopus System Parameters

Characteristics	Performance
Nominal operational frequency	26.8 GHz
Horn gain	23dB
Maximum transmit power	12.5 W
RF output power	0.7 W
High speed data input	Low voltage differential signaling
Modulation and coding	Full DVB-S2 specification
Volume envelope	(18 x 10 x 8.5) cm
Mass	820 g

Based on a link analysis [6], the summary of CubeSat achievable data rate at Ka-band is given in Table 10. The ground antennas are ranging from the small portable 1.2m/2.4m to apertures 5.4m, 7.3m, 11m, and 18m for Low Earth Orbit (LEO). For the analysis, the 18m station is at White Sands Complex (WSC) and the other antenna apertures are assumed at Alaska Facility (ASF).

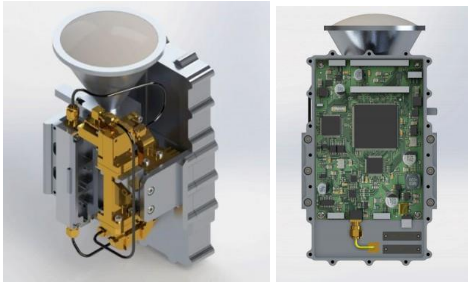


Figure 11: Canopus System

Table 10: Achievable Data Rate at Ka Band.

Ground Antenna	LEO Data Rate QPSK*	Data Rate LEO DVB-S2 **
ASF 1.2 m	477.5 kbps	16.943 Mbps
ASF 2.4 m	1.574 Mbps	55.847 Mbps
ASF 5.4 m	4.3 Mbps	153.4 Mbps
ASF 7.3 m	6.6 Mbps	233.2 Mbps
ASF 11 m	25.2 Mbps	892.9 Mbps
WSC 18 m	257.5 Mbps	1125 Mbps

* LEO (625 km) COTS QPSK Transceiver, 2W PA, earth coverage antenna of 4 dBi gain

** LEO (625 km) DVB-S2 Transceiver, 0.7 W PA, horn antenna of 23 dBi gain

CURRENT CUBESAT FLIGHT RADIOS AND ANTENNAS CAPABILITIES

The most critical components of a CubeSat communication systems are radios and antennas. Compact, power efficient, reliable radios and antennas will enable new mission classes or reduce the cost, schedules, and risk of current CubeSat mission design methodologies. One of the key challenges of CubeSat communication systems is finding NASA communication infrastructure compatible radios. Table 11 shows UHF-, S-, X- and Ka-band radios and NASA Network Compatibility; however this table presents just the vendor claims. In order to be considered as truly NASA NEN and SN compatible communication systems without flight heritage, a compatibility test with GSFC Compatibility Test Laboratory (CTL) is required. Some of the radios have been already tested and some of them are in the process of being tested.

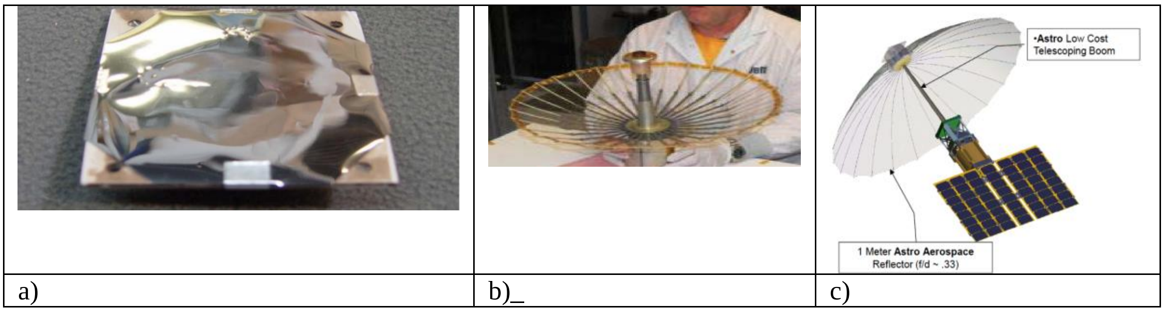
Table 11: Selected CubeSat Radios.

Freq.	Transceiver Name/Vendor	Size (cm)	Mass (g)	Flight Heritage or Future	Max. Data Rate	Modulation/FEC	NASA Network Compatibility
UHF-band	L3 Cadet UHF Tx	6.9 x 6.9 x 1.3	215	DICE, MicroMAS, CeREs	2.6 Mbps	BPSK	None
	ISIS Transceiver (ITRX)	9.6 x 9.0 x 1.5	85	Delfi-n3Xt	1.2 Kbps Downlink/9.6 Kbps Uplink	Rx AFSK/Tx BPSK	None
S-band	Innoflight SCR-100	8.2 x 8.2 x 3.2	300	Sense NanoSat CryoCube	4.5 Mbps	BPSK,QPSK,OQPSK GMSK,FM/PCM FEC: Conv. and R/S	NEN, SN, DSN
	Tethers Unlimited SWIFT-SLX	10 x10 x 3.5	380	iSAT	15 Mbps	BPSK	NEN,SN,DSN
	L3 Cadet S-Band Tx (CXS-1000)	6.9 x 6.9 x 1.3	215	None	6 Mbps	BPSK, QPSK, SOQPSK, SGLS M/FSK	None
	Nimitz Radio S-band Tx/UHF Rx	9 x 9.6 x 1.4	500	None	50 Kbps Downlink/1 Mbps Uplink	Uplink FSK, GFSK Downlink BPSK	None
	Quasonix nanoTX	3.2 x 8.6 x 0.8		CPOD	46 Mbps Downlink	PCM/FM, SOQPSK-TG, Multi-h CPM, BPSK, QPSK, OQPSK, UQPSK	NEN
	MHX-2420	8.9 x 5.3 x 1.8	75	RAX	230 Kbps Downlink/115 Kbps Uplink	FSK	Partially NEN
X-band	LASP/GSFC X-band Radio	9.8 x 9 x 2	500	None	12.5 Mbps Downlink/50 Kbps Uplink	BPSK/OQPSK R/S and Conv.	NEN
	Syrlinks/X-band Transmitter	9 x 9.6 x 2.4	225	None	5 Mbps	BPSK/OQPSK R/S and Conv.	NEN
	Marshall X-band Tx	10.8 x 10.8 x 7.6	<1000	FASTSat2	150 Mbps Downlink/50 Kbps Uplink	BPSK/OQPSK LDPC 7/8	NEN
	Tethers Unlimited SWIFT-XTS	8.6 x 4.5 (0.375U)	500	None	300 Mbps	{8,16A,32A}PSK	NEN,SN,DSN
	JPL /Iris Transponder	0.4U	400	INSPIRE	62.5 Kbps Downlink/1 Kbps Uplink	BPSK bit sync, CCSDS frame size	DSN, Partially NEN
Ka-band	Canopus Systems/ Ames Ka-band Tx	18 x 10 x 8.5	820	None	125 Mbps	{Q,8,16A,32A}PSK, DVB-S2, CSSDS, LDPC Concatenated with BCH	NEN,SN,DSN
	Tethers Unlimited SWIFT-KTX	8.6 x 4.5 (0.375U)	500	None	300 Mbps	{Q,8,16A,32A}PSK, DVB-S2, CSSDS	NEN,SN,DSN

CubeSat antennas are really critical components of CubeSats considering power, pointing and real estate limitations of CubeSat missions. CubeSat antennas mainly operate at UHF, S and X-band. Some CubeSats are starting to consider Ka-band systems. The below presents selected CubeSat antenna types at different operating frequencies.

Table 12: UHF-, S-, X- and Ka-band COTS CubeSat Antennas.

Antenna Vendor Name	Frequency	Antenna Gain (dBi)	Dimensions	Mass (g)
ISS Deployable	UHF	0	30 cm	100
Antenna Development Corporation S-Band Low-Gain Patch Antenna (LGA)	S	2	(4 x 4x0.25)"	115
Haigh Farr S-band Patch	S	2	(94x76x4) cm	62
BDS Phantom Works Deployable High Gain S-band Antenna	S	18	50 cm	1000
Antenna Development Corporation Micro Strip Array	X	>11	10x10 cm	28
BDS Phantom Works Deployable High Gain X-band Antenna	X	25	50 cm	1000
Canopus System Horn	Ka	25	18 cm	820



a) b)_ c)

Figure 12: a) Ant Dev Corp X-band Micro Strip Array b) USC's S- and X-band Deployable Reflector c)Astro Aerospace.

There is a need for a standard, robust and low cost CubeSat/SmallSat communication architecture for high data rate science missions. This takes advantage of both ground and CubeSat/SmallSat communication systems performance enhancements to achieve higher data rate end-to-end communication.

COMPATIBILITY TEST OF CUBESAT SOFTWARE DEFINED RADIO TRANSCEIVER THROUGH NEN AND SN

Software Define Radio (SDR) transceiver is the key device for future CubeSat/SmallSat communication need. The SDR transceiver will allow one radio platform to be re-configured and function across multiple operational characteristics such as data rate, frequency, modulation type and coding scheme and allow reducing payload mass, cost, and power for CubeSat/SmallSat missions. Compatibility test of a CubeSat SDR transceiver is planned in the summer of 2016 and in 2017 at the GSFC Communication Standard and Telecommunication Laboratory (CSTL) with SN and NEN. The SDR transceiver to be tested is COTS product currently at a TRL 4/5 minimum.

Compatibility Test Objectives:

The compatibility test is a collaboration between GSFC and industry aiming to increase the transceiver maturity level to TRL 6/7 at S, X and Ka-bands. The objectives of this task are:

1. Mature the SDR transceiver from TRL 4/5 to TRL 6/7, based on results of the compatibility test

2. Develop CubeSat/SmallSat requirements for SN/NEN communication

3. Conduct CSTL lab test, TDRSS end-to-end test, and NEN Wallops station compatibility test.

4. Perform vendor SDR transceiver assessment with respect to environmental, reliability, radiation tolerance, size/mass/power requirements

5. Where capability gaps exist, engage vendors to devise improvements that would allow them to meet the requirements

Today, there is a lack of certified standard NASA SN/NEN compatible CubeSat/SmallSat transceiver available, either developed by NASA or industry. Leveraging the efforts of industry in SDR development will benefit NASA in cost saving.

DESIRED CUBESAT TRANSCEIVER FEATURES

Based on results of the study with the proposed CubeSat/SmallSat communication architecture, the future CubeSat/SmallSat transceiver should be able to support SN/NEN S, X and Ka-band frequencies, BPSK, QPSK, rate ½ convolutional code, Reed-Solomon code, rate ½ LDPC code and high order modulation and coding (16 APSK, rate 7/8 LDPC code) for Space Science 10 MHz channel at X-band. The transceiver also should be able to support CDMA signal scheme with rate ½ LDPC code for CubeSat daughter/mother ship constellation inter-satellite link. The transceiver should be re-configurable and re-programmable for future communication needs. Adaptive modulation and coding capability is desirable for CubeSat mission under some circumferences.

OPERATION CONCEPTS FOR CUBESAT END-TO-END COMMUNICATION

Based on the analyses, signal trade studies and technology assessments, the operation concepts for future CubeSat end-to-end communications are derived.

1. CubeSat end-to-end communication requirements are able to be met with NEN stations at S & X band with practical patch antenna/earth coverage antenna and 1-2W PA

2. Adequate ground coverage and support time with NEN ground station

3. The transition from S to X-band and Ka-band NEN support depends on the flight hardware evolution

4. Higher data rate at X and Ka-band will reduce number of passes required

5. Software Defined Radio will provide flexibility for the standardization of CubeSat flight hardware that will reduce planning/testing costs and may reduce frequency authorization time

6. TDRSS can provide global coverage to CubeSats with low latency, compared to limited contact time with just ground stations. Send status alerts instantly without waiting until a ground station is in view

7. CubeSat-TDRSS support will be limited by lower data rate due to S/C power constraints

8. However, more coverage time allows using lower data rates to deliver more data than brief, intermittent ground station contacts. Ideal for emergency support

9. Use of TDRSS high rate support at Ka-band depends on flight high gain antenna evolution

10. The use of CDMA signal scheme for CubeSat daughter mother constellation inter-satellite cross link is good for those missions with coordinated orbit, for instance, formation flying

11. Through appropriate CDMA signal and CubeSat orbit design, it will be able to downlink adequate daily volume to the ground

12. The mother ship CubeSat will be a store-forward relay to downlink the science data to the ground either through NEN direct to ground link at X-band or through TDRSS K-band single access (KSA)

13. All CubeSats use GPS for position identification, i.e., the mother-daughter ship cross-links are not required to support tracking services

14. CDMA is able to provide ranging service with PN spread signal

15. Assume a mother to daughter ship forward link which is used to command the daughter ship to downlink science data to the mother ship and

to provide mothership position information to the daughter ship

16. For CubeSat unsynchronized flying (CubeSat are deployed out of the launch vehicle on no strict timeline and with no ability to station keep after being deployed), CDMA is not adequate to support the downlink of meaningful science data to the ground. Intelligent multiple access technique is needed to support those functions such as ad-hoc networking, cloud-based data routing, dynamic signal flow and protocol management.

17. High order modulation and bandwidth efficient coding (8-PSK, 16-APSK, 16- QAM, 32-APSK, 7/8 LDPC code, etc.) will enable higher data rate for the space science CubeSat mission at X-band that the spectrum allocation is constrained to 10 MHz.

18. While NASA NEN Ka-band ground station is limited for CubeSat high data rate support today, the X-band 10 MHz channel is an alternative to provide high data rates for Space Science CubeSat missions.

19. Among high order modulation schemes evaluated in this study, 16APSK is feasible since it only requires CubeSat to have a quasi-linear power amplifier, which can be done via pre-distortion compensation. Data rate up to 28 Mbps is achievable.

20. High rate LDPC code with low overhead to increase bandwidth efficiency is recommended for CubeSat NEN S-band 5 MHz channel communication links to achieve high data rate

21. High coding gain rate ½ LDPC code is preferred over the low overhead rate 7/8 LDPC code for earth science CubeSat high data rate missions which are in the order of no more than 100 to 200 Mbps. Bandwidth is not really a concern for a majority of earth science CubeSat missions at X-band 375 MHz channel.

NEN LUNAR CUBESAT SUPPORT

Lunar CubeSat missions will change the CubeSat paradigm since most of the CubeSats are designed and heavily used for LEO. Lunar CubeSat missions with NEN support will pave the way of CubeSat usage for the deep space missions. NEN offers high gain ground system solutions for lunar missions especially EM-1 and future exploration CubeSat missions with assets around the globe including NASA NEN and NEN commercial ground systems. The Space Launch System (SLS) will carry over 13 CubeSats to test innovative ideas along with EM-1 in 2018. Most of the EM-1 CubeSat missions propose to use the IRIS X-band radio with four X-band patch antennas, two for receive and two for transmit. Although some of the NEN commercial providers have X-band uplink capability, NASA NEN is considering adding X-band uplink capability to other NASA NEN stations. With this upgrade, EM1, EM2 and future CubeSat missions using X-band uplink radios can be supported. NEN offers high gain large ground systems that are spread around the earth for full coverage of L1/L2 and Lunar missions. In addition to X-band uplink, NEN also is considering adding cooled Low Noise Amplifiers (LNA's) to its current Ground Stations to enhance NEN Ground Systems G/T values by around 3 dB. Table 13 shows maximum achievable data rates with Wallops Ground Station (WG1) and Morehead State University (MSU) X-band Ground Systems with the below assumptions of 4 watts CubeSat output power and 12 dBi gain antenna at 400K km altitude and 3 dB enhancement with cooled LNA's. Wallops G/T is 34.5 dB/K and MSU G/T is 40 dB/K.

Table 13: Lunar Maximum Data Rate

Lunar Maximum Data Rate	Asset
10 kbps	WG1 without cryogenic LNA
20 kbps	WG1 with cryogenic LNA
40 kbps	Morehead 21m without cryogenic LNA
80 kbps	Morehead 21m with cryogenic LNA

NEN/SN CUBESAT SUPPORT STRATEGY

The NEN and SN are planning to enhance network assets to meet the needs of CubeSat mission requirements. Highlights of the NEN strategy include

1. Enhance CubeSat radios and NEN receivers to achieve high data rates for CubeSat missions

2. Maximize ground performance through cryogenic LNAs

3. Perform compatibility test to standardize NASA SN/NEN compatible CubeSat/SmallSat transceiver

4. Assist missions moving to X, S and Ka-band

5. Add/modify small aperture antennas
6. Add X-Band Uplink
7. Capitalize on Commercial Service Providers (CSP)/Academic Partnerships including small apertures, large apertures and X-Band uplink
8. Continue to engage with the CubeSat community

SN/Tracking and Data Relay Satellite Systems (TDRSS) can provide continual coverage of CubeSats compared to very limited contact time with just ground stations. Continual coverage can be used by CubeSats to send status alerts instantly without waiting until a ground station is in view. CubeSat TDRSS support will be limited by lower data rate due to power constraint on the spacecraft and the distance between the spacecraft and the satellite relay. However, more coverage time allows using lower data rates to deliver more data than brief, intermittent ground station contacts.

Both NEN and SN are investigating streamlining mission planning, integration, and test, to save costs and reduce lead time.

Details of the NEN and SN CubeSat communication support is discussed in a separate paper titled “NASA Near Earth Network (NEN) and Space Network (SN) CubeSat Communications”, Scott H Schaire et al, International Space Operation Conference, Korea, May 16-20, 2016 [7].

Acknowledgments

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References

1. Near Earth Network (NEN) Users’ Guide, Revision 1, 453-NENUG, NASA/Goddard Space Flight Center, Greenbelt, MD, January 15, 2010.
2. Space Network Users’ Guide (SNUG), Revision 9,” 450-SNUG, NASA/Goddard Space Flight Center, Greenbelt, MD, August 2007.
3. CubeSat Near Earth Network (NEN) S and X-band Link Analysis, GSFC Internal report, Nancy Huynh, Exelis, Inc, December, 2014.
4. CubeSat Space Network (SN) Multiple Access (MA) and Single Access (SA) Link Analysis, GSFC Internal report , Nancy Huynh, Exelis, Inc, December, 2014.
5. Assessment of CubeSat Maximum Achievable Data Rate via NEN X-band 10-MHz Downlink, GSFC Internal report, Yuwen Zhang, Chital Patel, Exelis, Inc, January, 2015.
6. CubeSat Near Earth Network (NEN) Ka-band Link Analysis, GSFC Internal report, Nancy Huynh, Exelis, Inc, July, 2015.
7. NASA Near Earth Network (NEN) and Space Network (SN) CubeSat Communications”, Scott H Schaire et al, International Space Operation Conference, Korea, May 16-20, 2016.