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NASA Near Earth Network (NEN) DVB-S2 Demonstration Testing for Enhancing Data Rates for CubeSat/SmallSat Missions

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ABSTRACT

National Aeronautics and Space Administration (NASA) CubeSat/SmallSat missions are expected to grow rapidly in the next decade. As the number of spacecraft on a ground network grows, employing higher data rates could reduce loading by reducing the contact time per day required. CubeSats also need to communicate directly to earth from space from longer distances than low earth orbit (LEO). These challenges motivate the need for bandwidth and power efficient modulation and coding techniques.

Today, Digital Video Broadcast, Satellite Second Generation (DVB-S2) is a communications standard for larger satellites. DVB-S2 uses power and bandwidth efficient modulation and coding techniques to deliver performance approaching Radio Frequency (RF) channel theoretical limits. NASA's Near Earth Network (NEN) conducted a demonstration test at the Wallops Flight Facility in spring of 2019 for CubeSat/SmallSat missions for enhancing data rate performance in NASA's S-band 5 MHz channel. The goal is to upgrade NEN with DVB-S2 to increase science data return and enable greater numbers of CubeSats.

This paper presents the NEN DVB-S2 demonstration testing objectives and performance measurement results. Results of the demonstration testing are compared with evolving SmallSat/CubeSat radios. DVB-S2 S-band transmitter development concepts for SmallSats/CubeSats and use of DVB-S2 by future missions are discussed.

INTRODUCTION

As of January 2019, there have been over 2100 CubeSats and nanosatellites launched according to nanosats.eu[1]. Figure 1 shows Planet Labs Flock 1 CubeSats being deployed from the International Space Station (ISS).

NASA CubeSats are used for Earth, Heliophysics, Astrophysics, and Planetary science and for space technology advancement. The NASA Goddard Space Flight Center (GSFC) continues to study methods to provide the highest data rate communication from the longest distance from earth with the least size, weight and power (SWaP) for NASA spacecraft to maximize the science and technology advancement return.

In spring of 2019, NASA Near Earth Network (NEN) conducted a Digital Video Broadcast, Satellite Second Generation (DVB-S2) demonstration, testing over the NEN 5 MHz channel at Wallops. DVB-S2 is a family of modulations and codes for maximizing data rate and minimizing bandwidth used and SWaP. DVB-S2 uses power and bandwidth efficient modulation and coding techniques to deliver performance approaching theoretical limits of RF channels. This paper describes the demonstration objectives, and performance measurement, test configuration and results. The DVB-S2 simulation analysis for the expected maximum data rate performance over the 5 MHz channel and link margin analysis with a typical CubeSat communication system are presented. Comparison of results of the

demonstration test with evolved SmallSat radios for data rate is presented. SmallSat DVB-S2 S-band transmitter development concept is discussed. In light of the results of the demonstration, this paper specifically addresses the potential use of DVB-S2 for spacecraft with NASA NEN ground stations.

Figure 1 Flock 1 is a constellation of CubeSats dedicated to Earth Observations achieving resolutions of three to five meters.[2]

The NASA Near Earth Network (NEN) Project consists of NASA, commercial, and partner ground stations, that provide direct-to-earth coverage in S-band, X-band, and Ka-band to Low Earth Orbit (LEO), Geostationary Earth Orbit (GEO), Highly Elliptical Orbit (HEO), Lunar orbit and Lagrange point L1/L2 orbit spacecraft up to one million miles from earth.

Figure 2 is a diagram of the NEN Project. The NEN currently supports approximately 40 NASA missions using about 40 ground stations at 17 sites worldwide.[3] Most ground stations are 11-meter class S-band and X-band, with one 18-meter S-band and Ka-band antenna. The NEN is adding additional Ka-band capability, and also operates two 6.1-meter S-band ground stations in Florida. The Ka-band and Florida ground stations are anticipated to augment NEN nanosatellite orbital tracking and communications capacity beginning in the early 2020 timeframe. Table 1 shows the Radio Frequencies that NEN supports via the National Telecommunications and Information Administration (NTIA).

Table 1 NEN Frequencies and Bandwidths for NTIA Licensing

Band	Function	Frequency Band (MHz)	Bandwidth (MHz)	Maximum Bandwidth per Transmitter (MHz)
S Uplink	Earth to Space	2,025--2,110	85	Typically <5
X Uplink	Earth to Space	7,190--7,235 (Two NEN sites to 7,200)	10	Typically <5
S Downlink	Space to Earth	2,200--2,290	90	5
X Downlink	Space to Earth, Earth Exploration	8,025--8,400	375	375
X Downlink	Space to Earth, Space Research	8,450--8,500	50	10
Ka Downlink	Space to Earth	25,500--27,000	1,500	1,500

Figure 2 NASA NEN Direct to Earth Coverage up to one million miles from Earth

DVB-S2 OVERVIEW

DVB-S2 has become a significant industry satellite communications standard.[4] The NASA NEN is interested in exploring upgrading the NEN with the current state of practice. The DVB-S2 framing structure allows for maximum flexibility in a versatile system and synchronization under low signal-to-noise ratio (SNR). The adaptive coding and modulation features allow optimization of transmission parameters for each individual user.

The DVB-S2 transmission system consists of 5 major Subsystems/Blocks:

- "Mode & Stream Adaption" Block
- "FEC Encoding" Block
- "Mapping" Block
- "Physical Layer (PL) Framing" Block
- "Modulation" Block

Figure 3 illustrates the subsystem block structure.

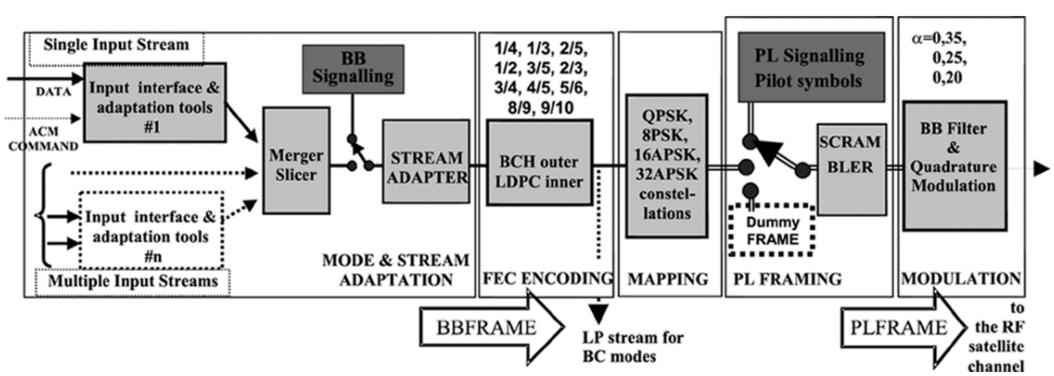

Figure 3 DVB-S2 Subsystem Block Structure

DVB-S2 Modulation & Coding

DVB-S2 defines a large number of modulation format and coding rate combination options:

- Modulation Schemes include: QPSK, 8PSK, 16APSK, and 32APSK
- Inner code: Low Density Parity Check (LDPC)
- Outer Code: Bose-Chaudhuri-Hocquenghem (BCH)

Table 2 summarizes DVB-S2 modulation and coding schemes

Table 2 DVB-S2 Modulation Schemes and LDPC Coding Rates

Modulation Schemes	LDPC Coding Rates
QPSK	1/4,1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10
8PSK	3/5, 2/3, 3/4, 5/6, 8/9, 9/10
16 APSK	2/3, 3/4, 4/5, 5/6, 8/9, 9/10
32 APSK	3/4, 4/5, 5/6, 8/9, 9/10

DVB-S2 General Characteristics:

- Baseband (BB) Filtering: I/Q symbol square root raised cosine filter (SRRC) with roll-off factors of 0.35, 0.25, or 0.20
- Bit interleaving applied to Forward Error Correction (FEC) for 8PSK, 16APSK, and 32APSK
- Randomization
- Optional pilot symbols to facilitate receiver synchronization
- Baseband frames
    - o 64,800 bits for application not too critical to delays
    - o 16,200 bits otherwise
- Very low SNRs with the DVB-S2 signal: Phase Noise could result in Carrier tracking loop cycle slips and Symbol synchronizer symbol slips.
- More stringent NEN user phase noise and symbol jitter constraints could reduce the possibility of cycle slips and symbol slips

DVB-S2 SIMULATION ANALYSIS FOR THE EXPECTED MAXIMUM DATA RATE PERFORMANCE IN THE NEN S-BAND 5 MHZ CHANNEL

The low rate LDPC 1/4, 1/3 and 2/5 coding performed in DVB-S2 requires low SNR, which in turn requires more stringent phase noise and symbol jitter to reduce the possibility of cycle slip and symbol slip. In consideration of these issues, DVB-S2 demonstration testing at Wallops did not include low rate LDPC 1/4, 1/3 and 2/5 coding. For rates 1/2, 3/5 to 9/10 LDPC coding with QPSK and 8PSK, DVB-S2 is not very sensitive to intermodulation and nonlinearity. 16 APSK and 32 APSK are sensitive to channel nonlinearity and intermodulation. But there are no particular issues with cycle slipping and symbol slipping for rates 2/3, and 3/4 to 9/10 LDPC coding. These signal schemes are expected to be appropriate for the NEN S-band channel.

Given the NEN S-band 5 MHz channel, what are the maximum achievable data rates for the variety of modulation and coding schemes in DVB-S2 signal family?

To predict the maximum achievable data rates, a bit error rate (BER) simulation taking into account the end-to-end channel condition and distortion of the NEN S-band 5 MHz channel is required. BER simulation is complicated and time-consuming; instead, a extrapolation estimate based on previous simulations in Tracking and Data Relay Satellite System (TDRSS) S-band 10 MHz and NEN X-band 10 MHz channels was used.[5] Table 3 presents the NEN station S-band channel distortion parameters.

Table 3 NEN Station S-band Channel Distortion Parameters Values

Parameter	Values
1. 1-dB RF Bandwidth	≥ 10 MHz
2. Gain Flatness (S-Band)	≤ 2.0 dB over 10 MHz
3. Gain Slope*	≤ 0.1 dB/MHz over ± 3.5 MHz
4. Phase Nonlinearity (Peak)*	≤ 3 degrees over ± 3.5 MHz
5. AM/PM	≤ 5 deg/dB
6. Antenna Subsystem Induced Phase Noise:	1 Hz – 10 Hz: ≤ 50.0° rms 10 Hz – 100 Hz: ≤ 10.0° rms 100 Hz – 1kHz: ≤ 2.0° rms 1 kHz – 3.5 MHz: ≤ 2.0° rms
* Bandwidth limitation for gain flatness, phase nonlinearity and gain slope: 70% of the signal main lobe width or 70% of the necessary bandwidth whichever is smaller.	

Results of the simulation analysis estimate for the predicated maximum data rate over QPSK/8PSK/16PSK and various LDPC/BCH coding rates for the NEN 5 MHz channel at S-band are depicted in Table 4.

Table 4 DVB-S2 Estimated Maximum Data Rate (Mbps) in the NEN S-band 5 MHz Channel

LDPC Coding Rate Modulation	1/ 2	3/5	2/3	3/4	4/5	5/6	8/9	9/10
QPSK	4.5	5.4	5.94	6.75	7.2	7.5	8.0	8.1
8PSK	6	7.2	7.92	8.6	10	11	12.2	12.6
16PSK	---	---	10.56	12	12.8	13.3	14.1	14.4

NEN DVB-S2 DEMONSTRATION TESTING OBJECTIVES

The demonstration testing of the DVB-S2 signal BER performance over the NEN S-band channel objectives were:

1. Determine the BER performance of the DVB-S2 signal and the maximum achievable data rate over the NEN S-band 5 MHz channel.
2. Collect E_b/N_0 versus BER data and signal spectra for NEN station medium loop configurations.
3. Determine implementation loss at various BER points by using collected E_b/N_0 versus BER data.

Demonstration Test Description and Configurations

The demonstration test was conducted with a Zodiac high data rate receiver (HDR) DVB-S2 demonstration license that contained a test modulator and receiver. Figure 4 depicts the demonstration test configuration. Figure 5 presents the test equipment for the demonstration configuration in the Microwave Laboratory at the Wallops Flight Facility. The test modulator, up converter, low noise amplifier (LNA) and the down converter emulates the NEN medium loop configuration.

During the medium loop test, the DVB-S2 signal generated by the test modulator at 720 MHz was up converted to the frequency of 8250 MHz. The 8250 MHz output of the up converter was coupled into the input of the LNA and to the down converter. The output

720 MHz IF signal of the down converter was connected to the receiver.

BER measurements were performed for the data rates depicted in Table 5. During all BER tests, the modulator was configured for the DVB-S2 modulation and coding schemes including QPSK, 8PSK and 16 APSK as well as various LDPC/BCH coding rates from 1/2 to 9/10 with a non-return to zero low (NRZ-L) data format on each channel. The test signal bandwidth was set to 5 MHz. Baseband frames were set to a 64,800 bit block. The pilot code was turned off. The modulator generated the Pseudo Random Bit Stream (PRBS) on each channel with baseband square root raised cosine (SRRC) filtering. In order to meet the NTIA spectral mask requirement, the SRRC roll-off factor was set to 0.20. There is no frequency dynamic for the test signal. The receiver was configured for the corresponding modulation and coding schemes for each BER measurement.

During the tests, a variable attenuator was used to vary the signal power in order to obtain E_b/N_0 values for BERs from 10^{-1} to 10^{-7}. BER vs. E_b/N_0 curves were plotted from the data points. The E_b/N_0 was calculated from the measured E_b/N_0. A spectrum analyzer was placed in parallel with the receiver input. The spectrum analyzer plot was stored on disk for each data rate.

Note that while the demonstration objective was for the NEN S-band 5 MHz channel, a HDR at the X-band frequency of 8250 MHz was used for the test. This was due to the Zodiac S-band CRT modem DVB-S2 demonstration license not being available at the time. However, as long as the test signal BW was set to 5 MHz, it was still appropriate for the demonstration objective.

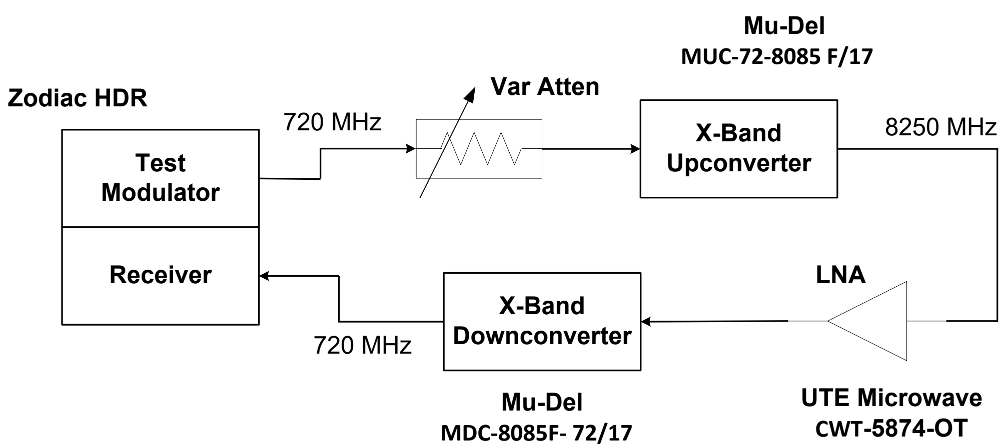

Figure 4 Demonstration Medium Loop Test configuration

Figure 5 Demonstration Test Hardware

DEMONSTRATION TEST RESULTS

The primary objective of the demonstration test was to determine the maximum data rate for DVB-S2 over the NEN S-band 5 MHz channel. The BER tests are the most critical measure in considering DVB-S2 signal structures to achieve higher data rates for the NEN channel.

BER measurements of twenty-one cases were performed for various DVB-S2 modulation and coding schemes. The maximum data rate determination is based on achieving an error free BER performance and meeting the NTIA 5 MHz spectral mask requirement for the data rate. Figure 6, Figure 7, Figure 8, and Figure 9 present results of the BER curves for select DVB-S2 modulation/coding schemes and data rates of interest.

The summary of implementation loss performance for all test cases is presented in Table 5. Implementation loss was obtained by subtracting the theoretical Additive white Gaussian noise (AWGN) curve from the actual measured curve. It reflects the loss due to channel distortion for the medium loop configuration.

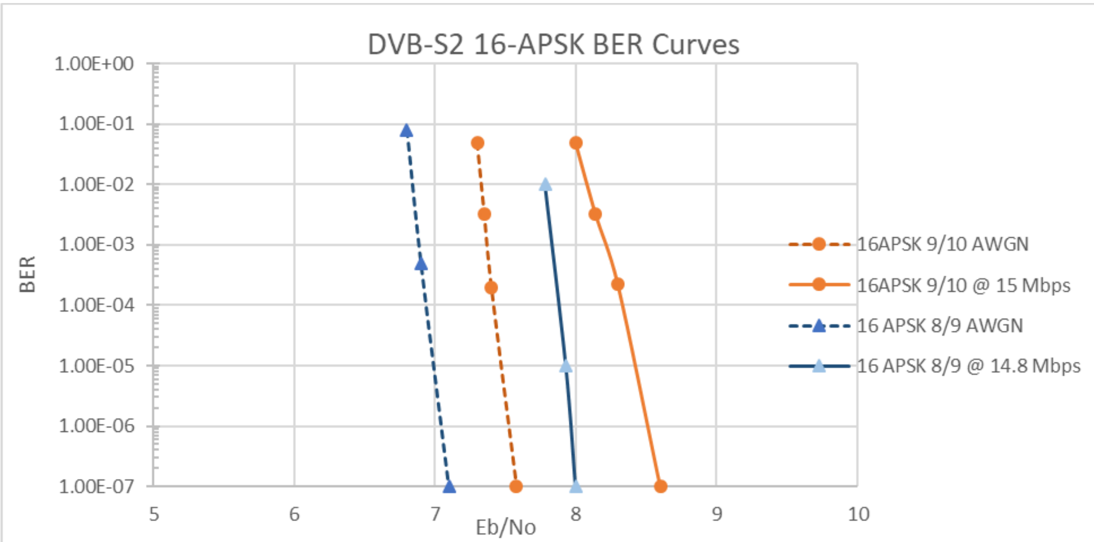

Figure 6 DVB-S2 16 APSK BER Curves

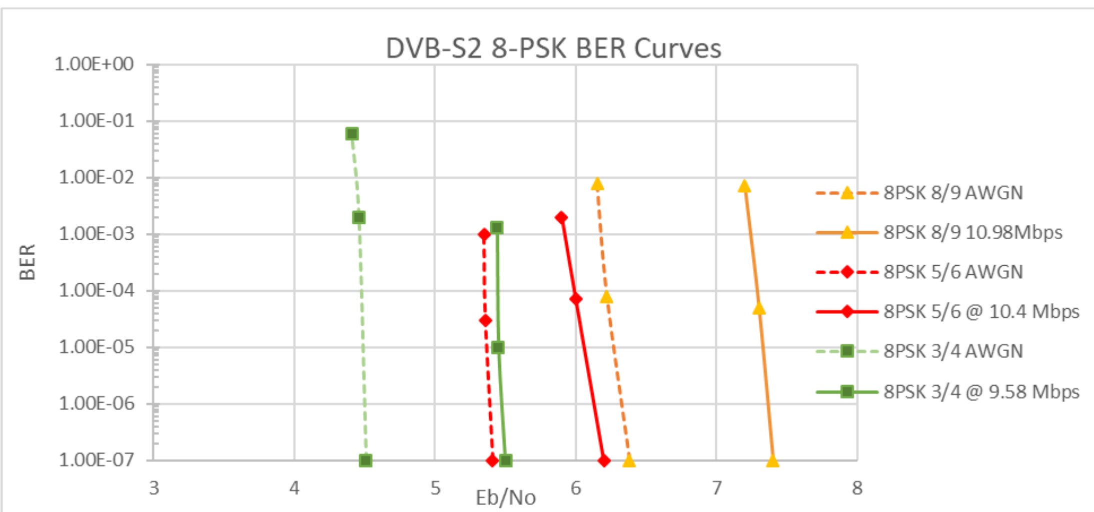

Figure 7 DVB-S2 8-PSK BER Curves

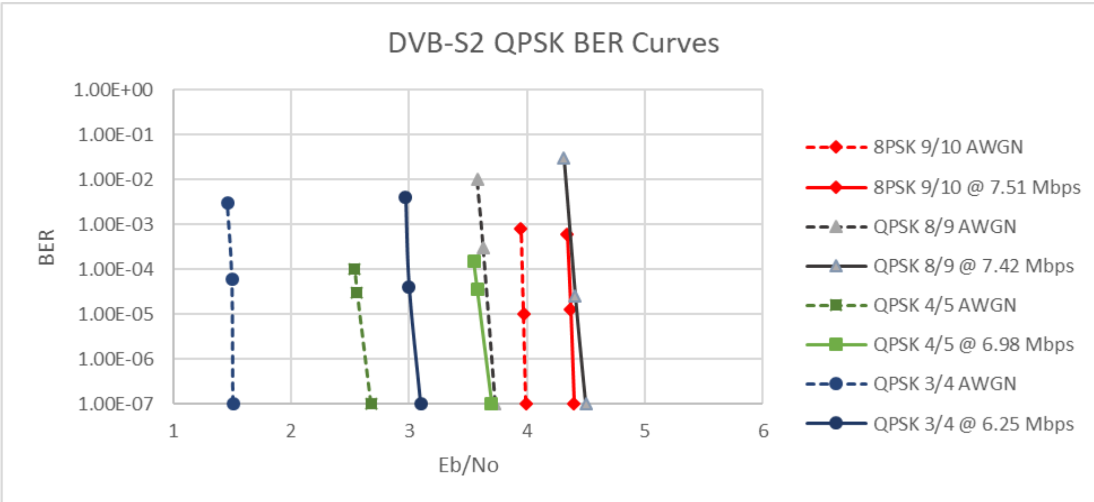

Figure 8 DVB-S2 QPSK BER Curves

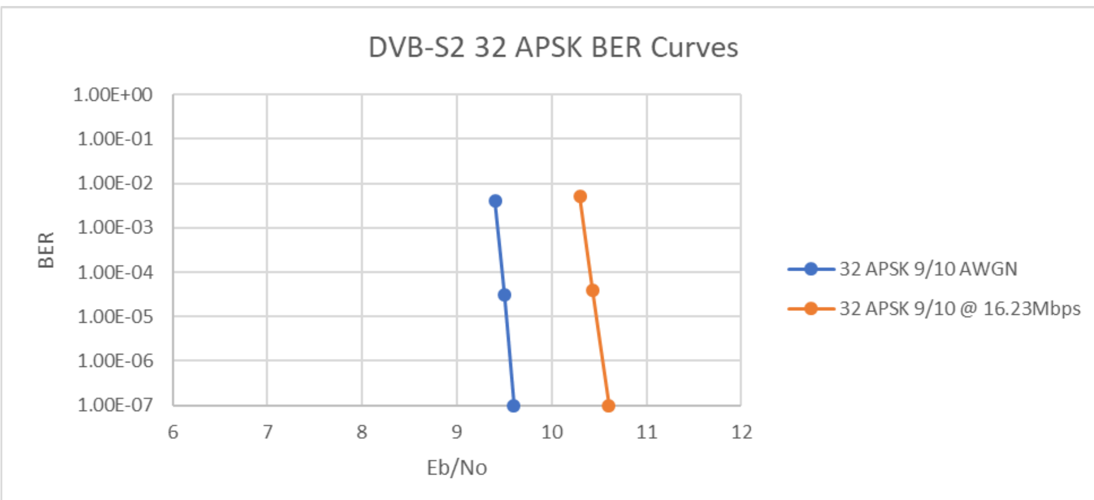

Figure 9 DVB-S2 32 APSK BER Curves

Table 5 Measured Data Rates (Mbps) and Implementation Loss Performance

LDPC Coding Rate Modulation and Loss	1/2	3/5	2/3	3/4	4/5	5/6	8/9	9/10
QPSK	4.38	5.23	5.95	6.25	6.98	7.12	7.42	7.51
Implementation Loss (dB)	0.8	1.4	0.5	1.0	1.12	0.62	0.7	0.5
8 PSK	-------	7.48	8.12	9.58	10.0	10.4	10.98	11.25
Implementation Loss (dB)	--------	2.5	1.45	0.5	0.6	0.6	0.9	0.8
16 APSK	---------	-------	10.81	12.3	12.46	13.86	14.8	15
Implementation Loss (dB)	---------	--------	2.3	1.8	1.2	0.8	0.8	1.0
Note: An additional BER test for 32 APSK 9/10 was performed. It achieved 16.23 Mbps with approximately 1 dB implementation loss.								

TEST RESULTS DISCUSSION

1. General Observation

Results of the DVB-S2 demonstration test are very good. The achievable data rates for QPSK, 8PSK and 16 APSK, 32 PSK modulation schemes with various code rates are well above the current data rates specification in the NEN Users Guide for the S-band 5 MHz channel with BPSK/QPSK and CCSDS convolutional and Reed Solomon (RS) coding.

2. BER and Implementation Loss Performance

The tests achieved a BER of less than 10^{-7} in the NEN station medium loop configuration for the DVB-S2 modulation and coding schemes selected. Error rate requirements for DVB-S2 are very stringent. As shown in Figures 6 to 9, the measured BER performances are within 1 dB from the excellent DVB-S2 FEC performance in the AWGN channel for various code rates and modulations, with FEC-coded blocks of 64,800 bits, for most test cases. The system achieves error free after achieving 10-7 with addition of a very few tenth of a dB. Implementation losses performance, as shown in Table 6 are less than 1 dB for high code rates and between 1 to 2 dB for low code rates in most test cases.

Implementation loss is the difference between the theoretical AWGN E_b/N_0 and the measured E_b/N_0. 16 APSK and 32 APSK are more sensitive to nonlinear distortions and may require nonlinear compensation in the uplink station. The results of mild implementation loss for the test cases of 16 APSK and 32 APSK indicate that the nonlinearly in the NEN medium loop configuration appears is not serious. Also, the DVB-S2 error correction capability is very good.

The slope of the BER curves for DVB-S2 concatenated LDPC and BCH codes are very steep and a small shift in SNR can significantly change the BER.

LINK MARGIN ANALYSIS FOR TYPICAL SMALLSAT COMMUNICATION SYSTEM USING DVB-S2 AT NEN S-BAND

A NEN down link margin performance analysis was performed for Smallsat/CubeSat missions at LEO using DVB-S2 signal schemes for the measured maximum data rates in Table 2.[6]

Table 6 is summary of the link margin performance.

Table 6 Link Margin Performance Analysis (Assume CubeSat 2W PA, 0 dBi antenna gain, Alt. = 600 km)

Mod/Rate/Margin	1/2	3/5	2/3	3/4	4/5	5/6	8/9	9/10
QPSK (Mbps)	4.38	5.23	5.95	6.25	6.98	7.12	7.42	7.51
Link Margin(dB)	14.45	13.25	11.77	12.44	10.79	10.40	9.48	9.16
8PSK (Mbps)	------	7.48	8.12	9.58	10.0	10.4	10.98	11.25
Link Margin (dB)	------	10.17	9.16	7.66	6.41	6.0	5.09	4.7
16APSK (Mbps)	------	------	10.81	12.3	12.46	13.86	14.8	15.0
Link margin (dB)	------	------	6.81	5.52	4.92	4.23	3.11	2.57

Overall, there is plenty of link margin for a SmallSat/CubeSat using DVB-S2 signal schemes with a typical communication system of a 2W PA and a patch antenna of 0 dBi gain. With a 5W PA and 6 dBi antenna gain, the link margin for 16 APSK 8/9 rate is 14.09 dB and for 16 APSK 9/10 rate is 13.55 dB. Note that the TechEdSat 8 has a 5W PA and an antenna of 6 dBi gain.

NEN SmallSat/CubeSat S-band Downlink Data Rate Analysis using DVB-S2 Signal Scheme at Lunar Orbit

A NEN down link data rate analysis was performed for a Smallsat/CubeSat at lunar orbit using DVB-S2 QPSK PC 1/4.[7]The Spacecraft parameter: 5W PA, antenna gain = 8.5 dBi, alt: 305,807 km. The link closes with 2dB margin.

Table 7 is data rates summary for NEN stations at White Sands, Swedish Space Corporation (SSC) Dongara and Wallops.

Table 7 Lunar SmallSat/CubeSat Data Rates at NEN Stations with DVB-S2 and a 5W spacecraft PA

NEN Stations	Data Rate (kbps)
White Sands 18m	366.4
SSC Dongara 13m	199.5
Wallops 11m	90.78

COMPARISON OF DVB-S2 RADIO BASED ON DEMONSTRATION TEST RESULTS WITH EVOLVED SMALLSAT RADIOS TESTED WITH THE NEN FOR DATA RATES AND PERFORMANCE

This section compares possible data rates with and without DVB-S2 with other radios that have been tested with NEN.

Table 8 presents NEN tested CubeSat radios and data rates.

Based on the results of the demonstration test, radio using DVB-S2 has advantages over radios with conventional modulation and coding schemes in the NEN S-band 5 MHz channel. DVB-S2 is capable of achieving much higher data rates with the same spacecraft Equivalent Isotopically Radiated Power (EIRP), relative to the same bandwidth. As shown in Figures 6 to 9, the difference between the measured BER performances and the theoretical AWGN limit is less than 1 dB for high code rates and between 1 to 2 dB for low code rates in most test cases.

Table 8 NEN Tested CubeSat Radios and Data Rates

Radio (Please contact the author for radio names)	Band	Power (W)	Data Rate from Low Earth Orbit (Mbps)	Bandwidth (MHz)	Test History
S-band Radio #1	S-band	2.0	1.0	2.0	Successfully compatibility tested in 2015
S-band Radio #2	S-band	2.0	2.0	4.5	Risk mitigation testing done in February and July, 2016
S-band Radio #3	S-band	1.0	1.0	2.0	Radio tested in 2016
X-band Radio #1	X-band	3.0	50.0	200.0	The SOCON spacecraft with the flight X-band communication system successfully downlinked 25 Mbps to the Wallops 11m in 2019.
S-Band Radio #4	S-Band	1.0	1.0	1.0	Radio successfully tested with Morehead State University Ground station in 2017
S-band Radio #5 without DVB-S2	S-band	2.0	5.0	5.0	Compatibility test was conducted successfully in 2018 at 120 Kbps and at 5 Mbps after a Software upgrade
S-band Radio #5 with DVB-S2	S-band	2.0	15.0	5.0	To be tested in 2020

The NEN made history after successfully tracking SeaHawk-1, the first ever CubeSat supported by the network, at a data rate of 25 megabits per second (Mbps), see Figure 10. On 4/30/2019, SeaHawk flew over the NASA Near Earth Network (NEN) station at Wallops Island, Virginia, and it broadcasted at a rate of 25 Mbps from a tiny antenna. SeaHawk-1 is a precursor for a constellation of CubeSats in the Sustained Ocean Color Observations using Nanosatellites (SOCON) mission that will observe ocean color in high temporal and spatial resolution modes.[8] Higher bandwidth is available for X-band for earth science for NEN than for S-band for all science and technology missions. DVB-S2 is capable of increasing data rates for X-band and Ka-band as well as S-band, relative to conventional modulation and coding schemes with the same spacecraft EIRP and same bandwidth.

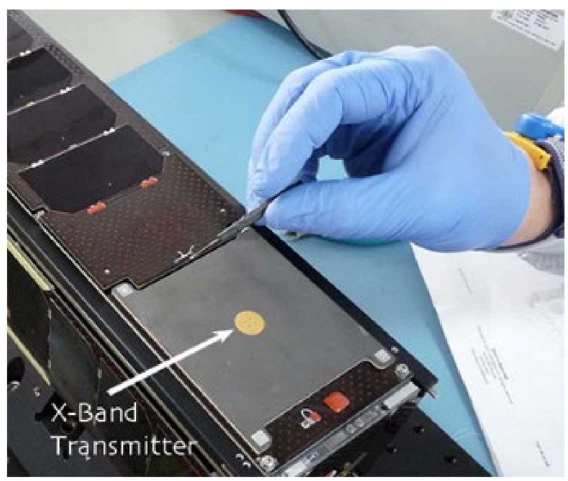

Figure 10 SeaHawk Radio Antenna

FUTURE MISSIONS AND DVB-S2

This section discusses potential future missions using DVB-S2. DVB-S2 can achieve much higher data rates in low-earth orbit over limited bandwidths in S-band compared to conventional modulations and coding schemes. DVB-S2 also has advantages for X-band and Ka-band in terms of data rate and power efficiency. For communication from lunar, Lagrange point distances and beyond, DVB-S2 has the potential to increase data rates relative to conventional modulation and coding schemes, due to better energy efficiency

Technical and Educational Satellite - 8, 9, 10 (TechEdSat-8, 9, 10)

CubeSats are an ideal method for advancing technologies. The TechEdSat-8 CubeSat is a collaborative project between San Jose State University (SJSU) and the University of Idaho with oversight from the NASA Ames Research Center. On January31st, 2019, TechEdSat-8 was deployed from the International Space Station (ISS), see Figure 11 .[9] TechEdSat-8 flew a NEN-compatible S-band radio, the Ettus Universal Software Radio Peripheral (USRP) B205 mini transceiver, see Figure 12.[10] It was unable to be flight tested with NEN due to power issues on-board the spacecraft.

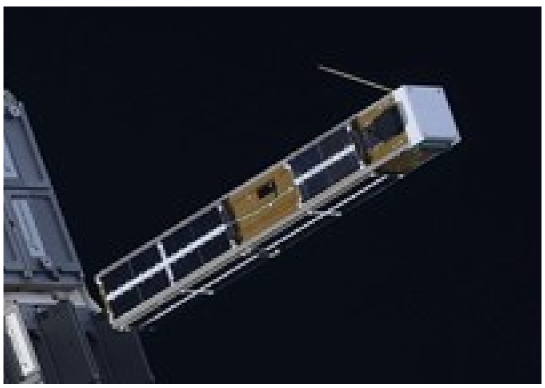

Figure 11 TechEdSat-8

Figure 12 B205-mini

The B205 Software Designed Radio (SDR) is a $1500 radio in the NEN frequency range of 2200-2290 MHz and it can support up to 56 Mbps. The radio is limited to 5 Mbps over a 5 MHz bandwidth allocation without bandwidth and power efficient modulation and coding schemes. With DVB-S2, as demonstrated at Wallops Flight Facility, 15 Mbps is achievable over a 5 MHz bandwidth. The Ettus B205 radio can be upgraded to use DVB-S2 with software and firmware implementation in the radio and flight computer system.

Table 9 shows that with a transmit output power of 7.4 dBW (5.5 Watts), with an external amplifier, and an assumed antenna gain of 8.5 dBi with pointing loss, a data rate of 4.4 Mbps is easily accomplished from a 400 km low-earth orbit, with plenty of margin, >22 dB, with the NEN Wallops 11m ground station WG1.

TechEdSat-8 was the first CubeSat to make use of a streamlined ground station compatibility test with the NEN Wallops Test Bed. The Wallops Test Bed was implemented at Wallops in 2018 and 2019 as the result of a Lean Six Sigma (LSS) study for streamlining the cost of ground station compatibility test. Near Earth Network (NEN) compatibility testing for the TechEdSat-8 mission was conducted at Wallops in October, 2018. Demodulation and data processing, spectrum capture, E_b/N_0 measurement, and radio frequency (RF) output power were tested. In addition, the antenna pattern was measured. See Figure 13.

TechEdSat-10 is launching in November 2019 and plans to demonstrate 5 Mbps with conventional modulation and coding schemes with the B205 radio. Compatibility Test will be rerun at Wallops in June 2019. TechEdSat-9, launching in December 2020, is planning to incorporate DVB-S2 and demonstrating 15 Mbps over a 5 MHz channel. Compatibility testing at Wallops is planned for TechEdSat-9 DVB-S2 radio in spring of 2020.

Table 9 TechEdSat-8 CubeSat Architecture-NEN S-band Downlink Margin Summary

Links	Information Rate (prior to any encoding)	Modulation	Coding	EIRP	S/C Altitude	Margin (Note 1 & 2)
S-band Downlink 11.3-m WG1	4.373 Mbps	SQPSK	Reed Solomon (RS)	14.3 dBW	400 km	22.3 dB
	2.1865 Mbps	BPSK				25.3 dB

Notes:
1. For RS downlink, the link margin is related to BER of 10^{-5} @ RS decoder.
2. Margin is relative to required BER for each scenario and does **NOT** include any required performance margin.

SmallSat DVB-S2 S-band Transmitter Development Concept

The radio for TechEdSat is an S-band transceiver utilizing an Ettus B205mini SDR radio and a 5W RF power amplifier. The transceiver currently supports a subset of CCSDS 131.0-B-3 “TM Synchronization and Channel Coding” and CCSDS 732.0-B-3 “AOS Space Data Link Protocol” and has been tested at Wallops using BPSK modulation at 120kbps and at Ames Research Center using QPSK at 5Mbps. The quadrature signal I/Q is generated by an Intel Edison x86 processor running at 500 MHz and sent to the Ettus B205mini SDR using a Universal Serial Bus (USB) 2 link.

The implementation of CCSDS 131.3-B-1 “CCSDS Space Link Protocols over European Telecommunications Standards Institute (ETSI) DVB-S2 Standard” for this transmitter will require these development phases:

1. Evaluation of existing open source Software implementations.
2. Integration and test in the GNU Radio.
3. Evaluation of the maximum achievable data rate when generating the quadrature signal from an Intel Edison processor.

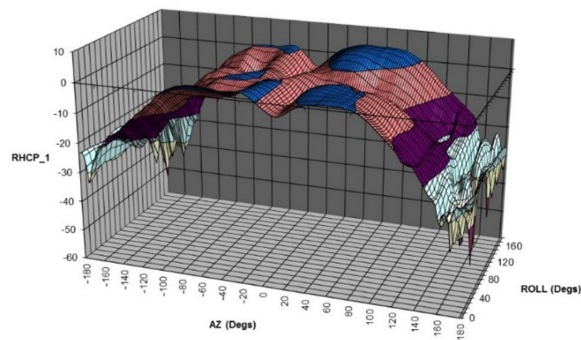

Figure 13 Three-dimensional Surface of TechEdSat-8 Antenna Pattern Centered at 2.28 GHz

4. Optimization of the data rate by moving some or all of the signal processing into the Ettus B205mini onboard Field Programmable Gate Array (FPGA).

Evaluation of Existing Open Source Software Implementation

The DVB-S2 16 APSK/LDPC 9/10 software modulator will be implemented in GNU Radio. As shown in Figure 14, the GNU Radio provides a sample implementation of a DVB-S2 transmitter.[11] This implementation is a good starting point as it contains most of the required blocs.

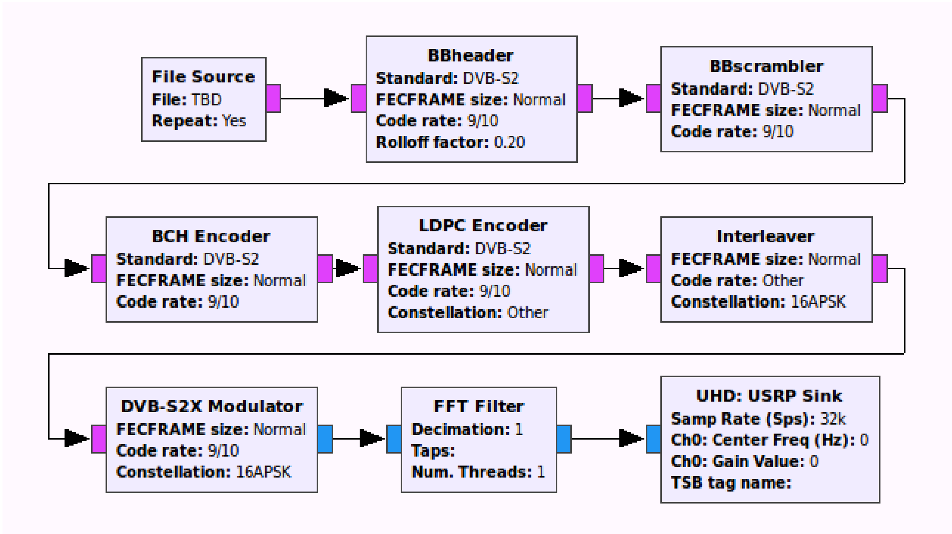

Figure 14 GNU Radio DVB-S2 Transmitter Implementation

GNU Radio Integration

Once all the open source libraries have been selected, the missing component will have to be designed, and integrated into a GNU Radio signal flow graph. The flow graph can be tested on a desktop machine prior to portage to the Intel Edison processor.

GNU Radio Profiling

The maximum data rate of the transmitter will depend on the Intel Edison processing power and on the bandwidth of the USB 2 link to the Ettus radio. This maximum data rate will be evaluated prior to any optimization along with the required processing power and bandwidth of each block in the flow graph determined.

GNU Radio Optimization

Based on the profiling results, the most CPU demanding blocks will be optimized until an acceptable data rate is achieved. Depending on the amount of required optimization, it may be necessary to implement some of the blocks into the B205mini FPGA. The Ettus radio frontend also includes a configurable output band-pass filter which can be used in place of any filtering done by the GNU Radio. Lastly it could be possible to pre-process the signal to transmit before a pass and transmit it during the pass with little processing power.

Engineering Development Unit Assembly

In order to facilitate development and testing, a stand-alone Engineering Development Unit (EDU) of the radio needs to be assembled. Such a unit has been assembled in the past for TechEdSat-8. The EDU encapsulates the Ettus B205mini radio, the RF power amplifier, an Intel Edison development board and a fan into an aluminum enclosure. The Intel Edison firmware can be updated on the field for the different NEN compatibility tests.

EDU NEN Compatibility Testing

The optimized DVB-S2 software/firmware modulator will be loaded into an Ettus B205mini EDU and tested at Wallops with a Cortex CRT receiver. The output power and BER will be measured and verified against the expected results demonstrated in this paper for NEN compatibility.

DVB-S2 Demonstration using the CubeSat Communications Platform (CCP)

The University of Alaska Fairbanks is currently developing the CubeSat Communications Platform (CCP), a LEO CubeSat mission that is expected to launch in 2022. The CCP mission goals include to demonstrate Retrodirective Antenna Array (RDA) on a CubeSat and evaluate its performance relative to gain, pointing, and power. Another goal is to demonstrate Variable coded modulation (VCM) through DVB-S2 with a NEN ground station and evaluate its performance in terms of information throughput. The RDA is an active phased array antenna with retrodirective steering capabilities that was developed as part of a NASA funded fellowship, and collaboration between the University of Alaska and NASA NEN. It is designed to autonomously determine the direction of arrival for an incoming interrogator signal, and perform beamforming to maximize the antenna gain in the direction of arrival.

Despite the highly dynamic environment due to variations in geometry for LEO missions, NEN currently supports missions that communicate with fixed channel codes, modulations, and symbol rates, resulting in a constant data rate that does not adapt to the dynamic link margin. The CCP will be the first mission to demonstrate Variable coded modulation (VCM) with a NEN ground station. VCM adapts to the dynamics of the link by transmitting at higher data rates when the signal-to-noise ratio (SNR) is high.

DVB-S2 for Lunar and Farther Distances

The NASA Cubequest Challenge awards prizes by meeting or exceeding technical objectives for communication from at least 4 million kilometers from Earth. Team Miles is competing and planning to fly the same B205 radio that TechEdSat missions will be testing in low-earth orbit for distances up to 10 million kilometers from earth using the NEN[10]. Table 10 shows that without DVB-S2, with a transmit output power of 7.4 dBW (5.5 Watts), and an assumed antenna gain of 8.5 dBi with pointing loss, a data rate of 205 kbps is accomplished from a 355,807 km lunar orbit with the NEN White Sands 18m ground station WS1. When DVB-S2 is used, the data rate increases to 366.4 kbps.[12] Similar increases are expected for further distances.

Table 10 Data Rates, With and Without DVB-S2 for Lunar Distances and Beyond

NEN Ground Station	Data Rate (bps)	Slant Range @ 5°EL (km)	With or Without DVB-S2
11.3-m WG1	26.6k	355,807	Without
11.3-m WG1	90.8k	355,807	With
18-m WS1	205.7k	355,807	Without
18-m WS1	366.4k	355,807	With
11.3-m WG1	210	4M	Without
18-m WS1	1.55k	4M	Without
18-m WS1	261	10M	Without

Expected Performance of Radios at Lunar Distances [using NEN]

The IRIS radio is a CubeSat radio designed for Lunar and further distances. Table 11 presents a comparison between the IRIS radio and the Ettus B-205 radio.

Table 11 IRIS Radio and Ettus B205 Radio Comparison

Radio/ Parameters	IRIS	Ettus B205mini
Cost	>$700k	$1500
Network Compatibility	DSN, NEN, SN*	NEN, SN
Input Power	0.5W – 38W	2.5 W
Output Power	X-band: 3.8W	10.0 mW
Size	568 cm^3 (0.5U)	42.0 cm^3
Mass	1100 g	24.0 g
Frequency Bands (TX)	X-band: 7.145 – 7.190 GHz (7.190 – 7.235 GHz)	100 MHz to 6 GHz
Frequency Bands (RX)	X-band: 8.4 – 8.45 GHz (8.45 – 8.50 GHz)	100 MHz to 6 GHz

DVB-S2 Support in X-band and Ka-band

DVB-S2 also has advantages for X-band and Ka-band. Syrlinks is working on developing CubeSat radios with DVB-S2 for X-band and Ka-band for high data rate applications.[13]

Table 12 shows the data rates for X-band and Ka-band with DVB-S2 using NEN 11m support at the Alaska station.[14]

Table 12 DVB-S2 X-band and Ka-band Performance

NEN Station	X-band	Ka-band
11m	580.8 Mbps *	931.1 Mbps**
* DVB-S2 QPSK 9/10, 2W PA, 11 dBi gain, 2 dB margin ** DVB-S2 QPSK 1 /2, 0.7W PA, 23 dBi gain, 2 dB margin		

CONCLUSION

DVB-S2 was demonstrated successfully over the NEN 5 MHz channel at Wallops. Results of the demonstration are very good. DVB-S2 achieves data rates much higher than conventional modulation and coding schemes for the same spacecraft EIRP relative to the same bandwidth. A DVB-S2 NEN compatible S-band transmitter is being developed now. NASA ARC is planning to incorporate DVB-S2 and demonstrate 15 Mbps over the NEN S-band 5 MHz channel for the TechEdSat 9 mission, to be launched in December 2020. University of Alaska also is planning to demonstrate Variable Coded Modulation (VCM) through DVB-S2 with a NEN ground station for the CubeSat Communications Platform (CCP), a LEO CubeSat mission that is expected to launch in 2022. DVB-S2 will increase science data return and enable greater numbers of NASA CubeSat missions and is a potential candidate signal scheme for lunar and Lagrange point missions.

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