An Evaluation of New Coding and Modulation Schemes for NASA Space Network

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As part of the effort to sustain the growth of the National Aeronautics Space Administration (NASA) Space Network (SN), additional coding and modulation schemes have been implemented in new NASA modems to increase the ground segment capabilities of the White Sands Complex (WSC) and to meet future customer needs. These new schemes, referred to as "non-legacy" modes, include low-density parity-check (LDPC) forward error correction codes and 8-ary Phase Shift Keying (8-PSK) modulation. Compared to legacy service modes and conventional signal structures, LDPC codes offer larger coding gains, thus providing additional link margins for power-constrained scenarios, and 8-PSK modulation increases spectral efficiency, enabling high data rate communications over bandwidth constrained channels such as the SN Tracking and Data Relay Satellite (TDRS) S-band channel. To evaluate these new modes for near-Earth communications, we have characterized the performance of various "non-legacy" coding and modulation combinations as implemented in the new NASA modems. We collected performance curves in a controlled laboratory environment followed by end-to-end testing over the TDRS channel. In this paper, we present our data and discuss our findings. In order to obtain the full coding gains offered by the new schemes, the new modems must be able to work in a lower signal-to-noise ratio than the operating range of existing service modes. Our results show that the new modems are able to perform within 1-2 dB of the theoretical performance with the new codes. For modes where the implementation loss could be further reduced, we suggest ways for improvement.

I. Introduction

The National Aeronautics Space Administration (NASA) is in the process of replacing legacy equipment in the Space Network (SN) ground terminal at the White Sands Complex (WSC) through the User Services Subsystem Component Replacement (USS CR) project. This effort includes replacing legacy receivers with new narrowband (NB) and wideband (WB) modems. The new USS CR modems support not only legacy signaling formats[1] in order to provide backward compatible services for existing customers, but also new coding and modulation schemes not previously offered by the SN. In this work, we evaluated the performance of non-legacy modes as implemented by

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the USS CR NB modem with a focus on low-density parity-check[2,3] (LDPC) forward error correction codes (FEC) when used together with quadrature or 8-ary Phase Shift Keying (PSK) modulations[3,4].

We tested the NB modem qualification model in the lab using a Tracking and Data Relay Satellite (TDRS) channel emulation filter and over-the-air via the actual TDRS channel. For each scenario we compare the measured data with theoretical performance. Through our results, we show that despite variations in the implementation loss for each coded modulation scheme, the NB modem can realize the benefits of the new technologies for future NASA missions.

The paper is organized as follows: Section II lists the test cases and gives a brief rationale for each case selection. Section III describes the test configurations for lab testing and for end-to-end TDRS testing. Section IV presents the modem performance measured in a controlled lab environment. Section V reports the modem performance measured over the actual TDRS channel. Section VI summarizes our findings. Section VII discusses further options to improve the performance of the NB modem.

II. Measuring the NB Modem Performance in Non-legacy Modes

The NB modem was designed for the S-band channel. We first characterized the NB modem performance in the lab using an Additive White Gaussian Noise (AWGN) generator and a bandlimited TDRS emulation filter. The specifications of the emulation filter are given in Appendix A. We then conducted end-to-end testing over the actual TDRS channel repeating selected scenarios tested in the lab. Even though the uplink antenna did not emulate all of the distortions that could be found in a customer spacecraft, end-to-end testing did include other signal impairments that are typical in a downlink pass. Lab testing took place in the Hardware Maintenance Depot (HMD) and TDRS testing occurred in the Space Link Ground Terminal (SGLT). Both facilities are located at NASA WSC.

A. LDPC Codes and 8-PSK Modulation

In our modem evaluation, we concentrated on non-legacy LDPC coding and 8-PSK modulation schemes. Binary LDPC codes are "soft-decision" decoded by iterating on the likelihood ratios of demodulated symbols until the symbol decisions converge to a valid codeword or until an error is declared because the maximum number of iterations is reached**.** LDPC codes have been shown to outperform legacy convolutional code, Reed-Solomon (RS) code, or their concatenation with comparable code parameters. The Consultative Committee for Space Data Systems (CCSDS) has standardized a list of LDPC codes[5] that includes the (2048,1024) rate ½ and (8160,7136) rate 223/255, or approximately rate 7/8 LDPC codes. The first number in the brackets is the codeword length in bits, and the second number is the information length in bits. The code rate is the ratio of the second number to the first. The NB modem has implemented encoders and decoders for these two codes. The rate ½ code is used for a power constrained communication channel, and the rate 7/8 code is used for a bandwidth constrained channel.

When a customer requires a high data rate link to the ground, 8-PSK modulation can be used in place of quadrature PSK (QPSK) to increase bandwidth efficiency. However, the TDRS S-band Single Access Return (SSAR) channel is bandpass filtered. We measured the effects of this bandlimiting on the modem performance when running the new coding and modulation schemes.

B. Modem Test Cases

Table 1 lists the test cases that we have covered in the lab and over the TDRS channel. The first and second columns of the Table group the test cases by Data Group (DG) and modulation. DG1 Mode 2 is a non-coherent service and uses Staggered Quadrature Pseudo Noise (SQPN) modulation where data on each I and Q channel is spread by a short PN code with a period of 2^{10}-1 and a frequency of approximately 3Mchips/sec[6]. DG2 is direct M-ary PSK transmission. We tested Staggered QPSK (SQPSK) and 8-PSK. Each modulation was used together with a forward error correction (FEC) code listed in the third column. The data rate tested in symbols per second is given in the fourth column. Symbols include attach sync markers (ASM), information bits, and parity bits. For example, when the data rate is 384ksps for the rate ½ LDPC code, the information rate is $384k\,\frac{1024}{2112} = 186.18k$bits per second (bps). The rate ½ LDPC code encodes 1024 information bits into 2048 codeword symbols and each codeword is prefixed by a 64-bit ASM before transmission.

We mark the test cases conducted in the lab in the fifth column. Since the available airtime for TDRS testing was limited, we repeated only a few test cases over TDRS and those are marked in the sixth column.

In spread spectrum mode (DG1M2), we collected uncoded and convolutional coded (CC) performance. We used the results to benchmark the NB modem against the legacy Integrated Receiver (IR) and to calibrate test equipment. For the rate ½ LDPC code, we measured the modem performance at a wide range of data rates from the very low

2ksps to the maximum allowed data rate 600ksps for this mode. For the rate 7/8 LDPC code, we only collected data at the maximum data rate.

In DG2 mode we tested SQPSK and 8-PSK modulations together with LDPC codes. For the rate ½ code, we covered data rates from 1Msps to 18Msps. For the rate 7/8 LDPC code, we covered a low data rate 600ksps and a high data rate 12Msps mode. Results for high data rates will quantify the impact of TDRS bandlimiting on the modem performance.

Data Group	Modulation	FEC	Data Rate (sps)	Offline Lab Testing	TDRS End-to-end Testing	Notes
DG1M2 (spread spectrum)	SQPN	none	384k	✔		1
		CC(7,1/2)	384k	✔		1
		LDPC ½ with information length 1024 bits	2k	✔		2
			72k	✔	✔	3
			384k	✔	✔	-
			600k	✔	✔	4
		LDPC 7/8	600k	✔	✔	4
DG2 (direct Phase Shift Keying)	SQPSK	LDCPC ½ with information length 1024 bits	1M	✔	✔	-
			2M	✔		-
			12M	✔	✔	5
			18M	✔	✔	6
		LDPC 7/8	600k	✔		-
			12M	✔	✔	5
	8PSK	LDPC ½	24M	✔		-
		LDPC 7/8	27M	✔	✔	7

Table 1. NB modem test cases.

Notes:
1. Legacy modes to benchmark the NB modem and calibrate test equipment
2. Very low data rate for DG1M2 spread spectrum modulation
3. Low data rate for DG1M2 spread spectrum modulation
4. Maximum data rate allowed by DG1M2
5. Maximum data rate for the Integrated Receiver
6. Very high data rate for DG2 SQPSK modulation
7. Only achieved 500kbps over TDRS limited by the available carrier power on day of test

III. Test Configuration

A. Lab Measurements

The test configuration for lab testing is given in Figure 1. The primary path was to measure the performance of the NB modem. The parallel path was to measure the performance of the legacy IR and we use this measurement to benchmark the NB modem. The Performance Measuring and Monitoring System (PMMS) Test Equipment (PTE) was used to generate a PN sequence and to serve as the test modulator. The output of the PTE was fed into a 10MHz wide filter (with specifications listed in Appendix A) centered at the 370 MHz Intermediate Frequency (IF).

This filter has a magnitude and phase response that emulated some of the distortions found in the TDRS S-band channel. A Noisecom additive white Gaussian noise (AWGN) generator was used to create the appropriate amount of AWGN for the given PTE carrier power to achieve the desired signal-to-noise ratio (SNR). This noise is added to the filtered output to create the received signal, which was fed via a splitter into the NB modem and the IR for demodulation. With LDPC codes enabled, the NB modem decoded the demodulated stream using the built-in decoder and computed the codeword and bit error rates. The decoded bits were also forwarded to an external bit error rate tester (BERT) to validate the bit error reporting by the NB modem.

The legacy IR cannot decode LDPC codewords. In this case, we used an external LDPC decoder working on soft symbols with 5-bit quantization to decode. The decoder computed codeword error rates but the bit error rate was calculated by an external BERT based on the decoder output.

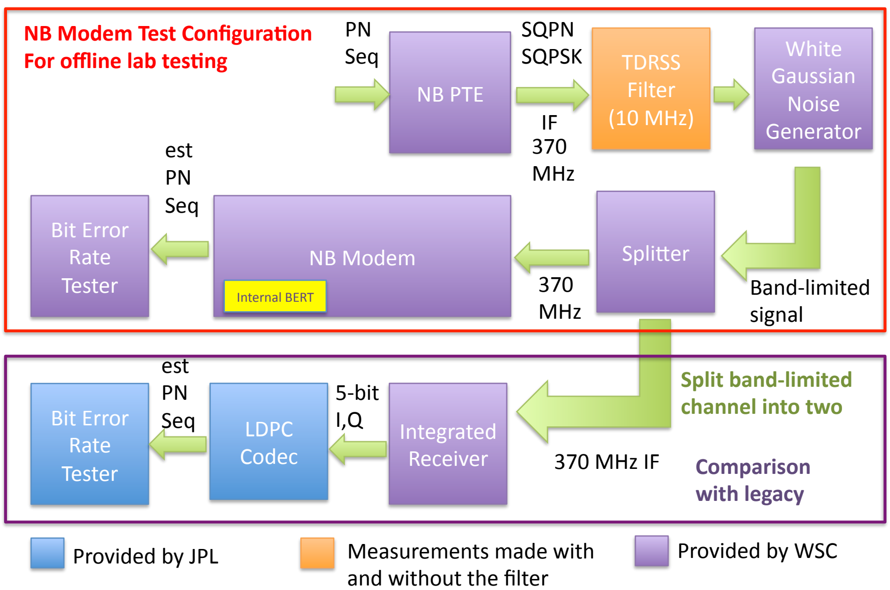

Figure 1. Test configuration for in-lab testing of the NB modem.

B. TDRS Measurements

The configuration for end-to-end TDRS testing is given in Figure 2. We did not measure the IR performance and only conducted NB modem testing. Again, the PTE was used to generate a source PN data and to modulate the signal, which was up-converted and transmitted by the WSC uplink chain at 2,287.5MHz. A TDRS collected and returned the transmitted signal at 13,677.5MHz. The WSC downlink chain received and down-converted the RF signal to IF for demodulation and decoding by the NB modem. We recorded the codeword and bit error rates reported by the NB modem and compared the results to the modem performance measured in the lab on the AWGN channel and using the TDRS channel emulation filter.

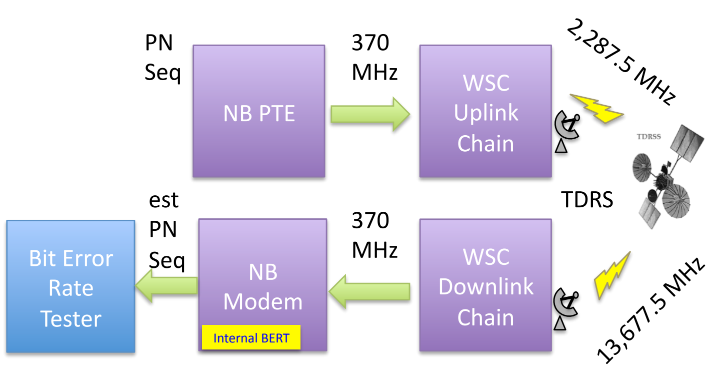

Figure 2. Test configuration for end-to-end TDRS testing of the NB modem.

C. NB Modem Configuration

The NB modem offers a lot of flexibility and many of its configuration parameters can be changed. The loop bandwidths for carrier acquisition and tracking, and for symbol acquisition and tracking can be adjusted. When a block code is applied, the thresholds used by the frame synchronizer to transition between search and check, check and lock, and lock and search states can be tuned. Modifying the modem configuration parameters to improve the modem performance in one area will often tradeoff performance in another area. For example, narrowing the carrier tracking loop bandwidth will increase the noise rejection of the carrier tracking loop, but will make the modem less tolerable to spacecraft Doppler. This paper does not explore these performance tradeoffs. Instead, all of the measurements were made with the factory recommended "auto" setting.

IV. NB Modem Performance Data – Lab Measurements

In this Section, we present data gathered by measuring the NB modem performance in a controlled lab environment. To evaluate the NB modem, we first benchmarked the NB modem against the IR in legacy modes. We also collected modem performance when it was configured for spread spectrum, SQPSK, or 8-PSK modulation with either the rate ½ or the rate 7/8 LDPC code. The modem performance was measured on the AWGN channel and then with the TDRS channel emulation filter. We quantify the modem implementation loss by comparing the measurements against the theoretical performance curves.

A. Spread Spectrum SQPN Modulation

SQPN modulation is a legacy service[6]. We plot in Figure 3 the performance of the IR and the performance of the NB modem without FEC coding (marked by solid-circles) and with the (7,1/2) convolutional code[5] (CC) (marked by x's) on the AWGN channel. The modem was configured for a data rate of 384ksps. In the uncoded case, one information bit is one codeword symbol and in the rate ½ convolutional code case, one information bit corresponds to two codeword symbols. The horizontal axis, given in decibels (dB), represents the signal-to-noise ratio (SNR) or the ratio of the minimum energy per information bit (Eb) over the single sided noise power spectral density (N0) and the vertical axis represents the bit error rate (BER). A point in the plot marks the minimum Eb/N0 that is required at the input of the modem to achieve the corresponding BER at the output of the modem. Since we could not afford to measure the performance of every operating point, we extrapolate a performance curve by connecting the measured data points.

When compared to the theoretical uncoded performance at a BER of 1e-5, the NB modem exhibited a very small implementation loss and was about 0.8 dB better than the IR. When compared to the theoretical CC(7,1/2) performance at the same BER, the NB modem carried approximately a 0.5 dB implementation loss and was again better than the IR, which produced about a 1 dB implementation loss. To demonstrate the benefits of a new mode supported by the NB modem, we also provided the modem decoding performance for the rate ½ LDPC code. At a BER of 1e-5, the NB modem achieved a coding gain of more than 1.8 dB when using a rate ½ LDPC code versus when using the rate 1/2 convolutional code. The NB modem legacy performance is summarized in Table 2.

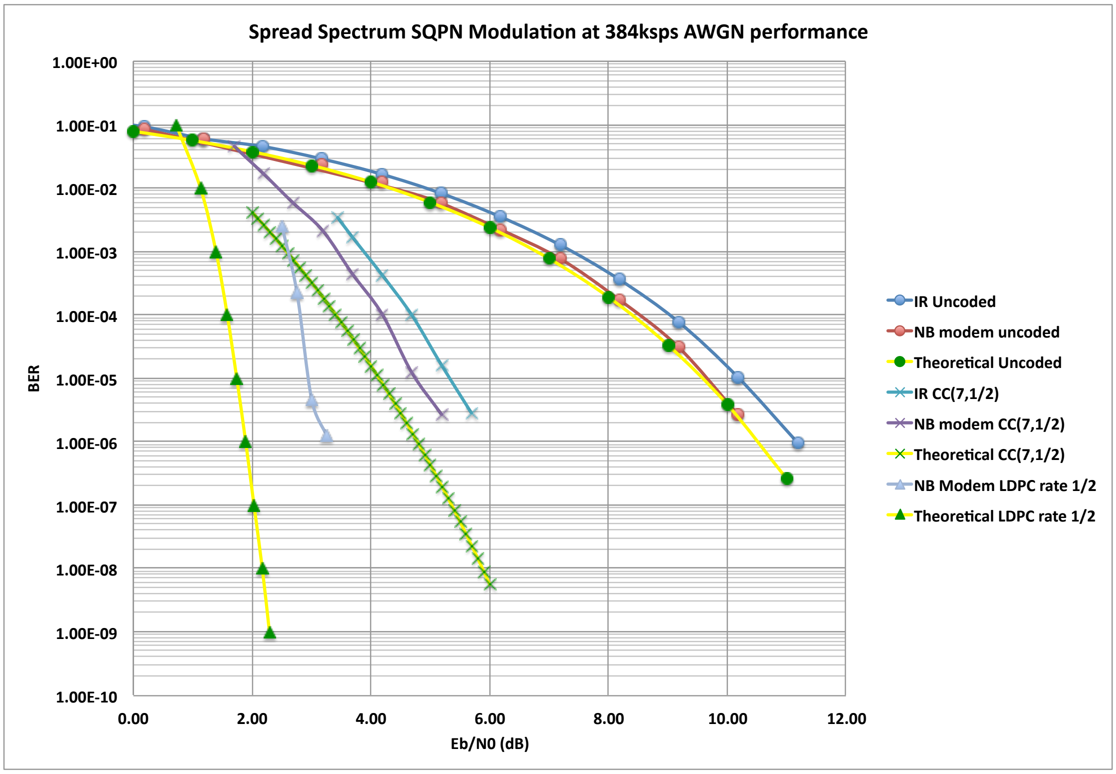

Figure 3. Modem performance in DG1M2 on the AWGN channel.

NB Modem Implementation Loss @ BER of 1e-5	
Uncoded	Convolutional Code (7,1/2)
< 0.1 dB	0.5 dB

Table 2. NB modem DG1M2 gap from theoretical performance at a BER of 1e-5 on the AWGN channel.

B. Spread Spectrum SQPN Modulation with LDPC Codes

We plot the NB Modem performance with spread spectrum SQPN modulation and LDPC codes in Figure 4. The codeword error rate (WER) curves for the rate ½ LDPC code are denoted by triangles and for the rate 7/8 LDPC code are denoted by squares. The WER is computed by taking the ratio of the number of decoding trials that failed to produce a valid codeword over the total number of decoding trails that took place in one experiment. The yellow lines mark the theoretical performance for each code and dashed lines identify the curves measured using the TDRS channel emulation filter.

The modem decoding performance for the rate ½ LDPC code for the most part was independent of the data rate as seen in Figure 4. The implementation loss at a WER of 1e-4 is approximately 1.2 dB for most data rates. But the NB modem seemed to exhibit an additional 0.5 dB of implementation loss when the data rate was at 2ksps. This data point highlights the difficulty of designing a modem to work well when the data rate is low because the amount of data available for parameter estimation is small. When the TDRS filter was used, an additional 0.8 dB of implementation loss was observed for both 384ksps and 600ksps. Even though PSK modulations at these data rates generate signals with energy that mostly reside in the filter passband, in DG1 modes data is spread by a 3Mchip PN sequence[6] and the modulated signal will have a wider spectrum and be affected by the TDRS channel emulation filter leading to a degraded receiver performance.

For the rate 7/8 LDPC code, the NB modem decoding produced a 0.7 dB implementation loss in the AWGN channel and similar to the decoding of the rate ½ code, an additional 0.8 dB implementation loss was measured when the TDRS channel emulation filter was used.

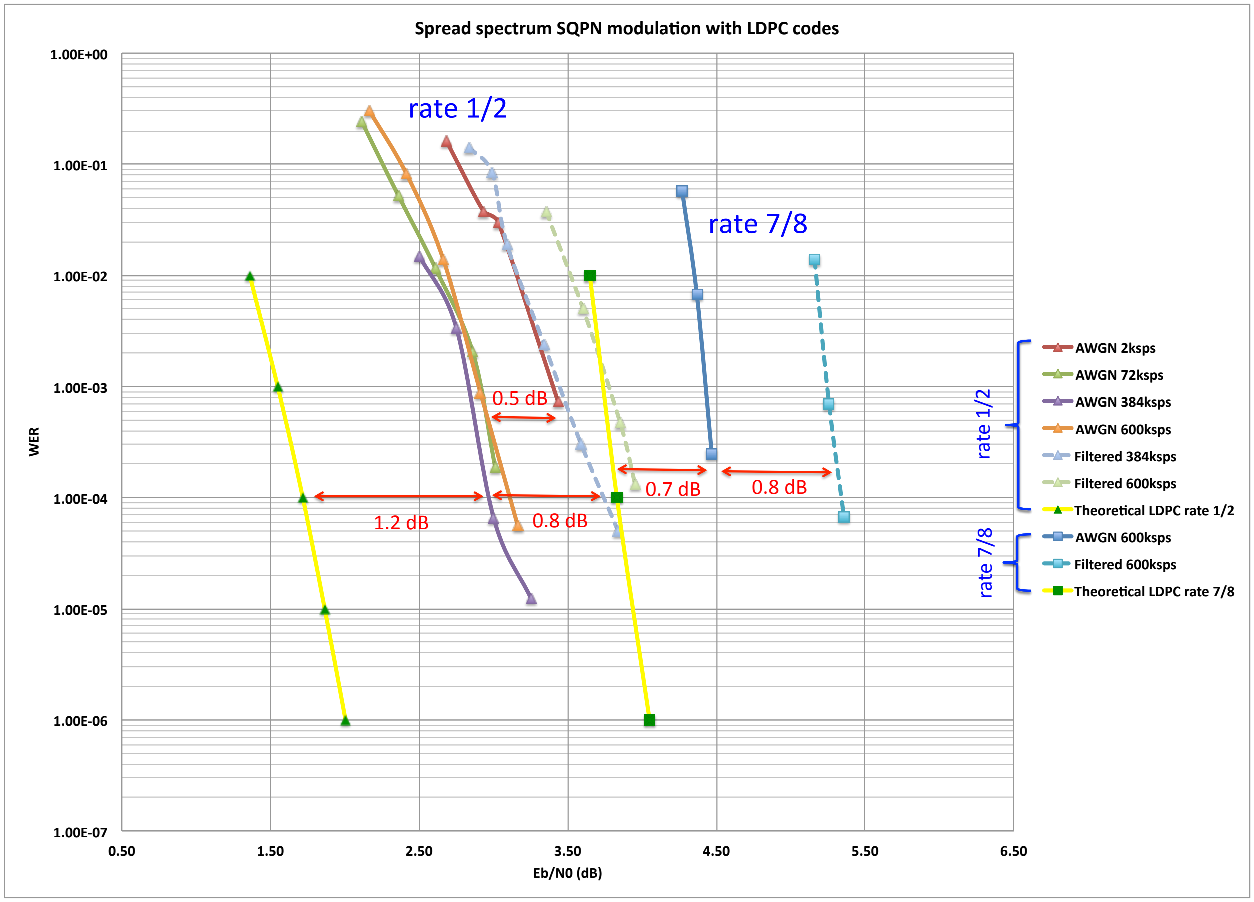

Figure 4. NB modem performance in DG1M2 using LDPC codes. The curves for the rate ½ LDPC code are denoted by triangles. The curves for the rate 7/8 LDPC code are denoted by squares. Solid curves are the performance measured on the AWGN channel. Dashed curves are the performance measured on the emulated TDRS channel.

C. SQPSK Modulation with LDPC Codes

We plot the NB modem performance curves for DG2 SQPSK modulation with LDPC codes in Figure 5. Again, the yellow lines give the theoretical performance for each code and the dashed lines identify the performance measured with the TDRS channel emulation filter.

For the various data rates tested, the NB modem produced very similar decoding performance curves. The implementation loss for the rate ½ LDPC code on the AWGN channel was approximately 1 dB. For a data rate of 12 Msps, we also characterized the decoding performance when the TDRS channel emulation filter was used. The additional modem implementation loss due to bandlimiting was 1.8 dB.

The implementation loss for the rate 7/8 LDPC code on the AWGN channel was about 0.5 dB. As expected, the TDRS channel emulation filter did not impact performance at low data rates and the modem decoding performance with filtering at 600ksps was approximately the same as the AWGN performance. The effects of bandlimiting distortion became significant at a higher data rate and the implementation loss for 12 Msps was 2.2 dB.

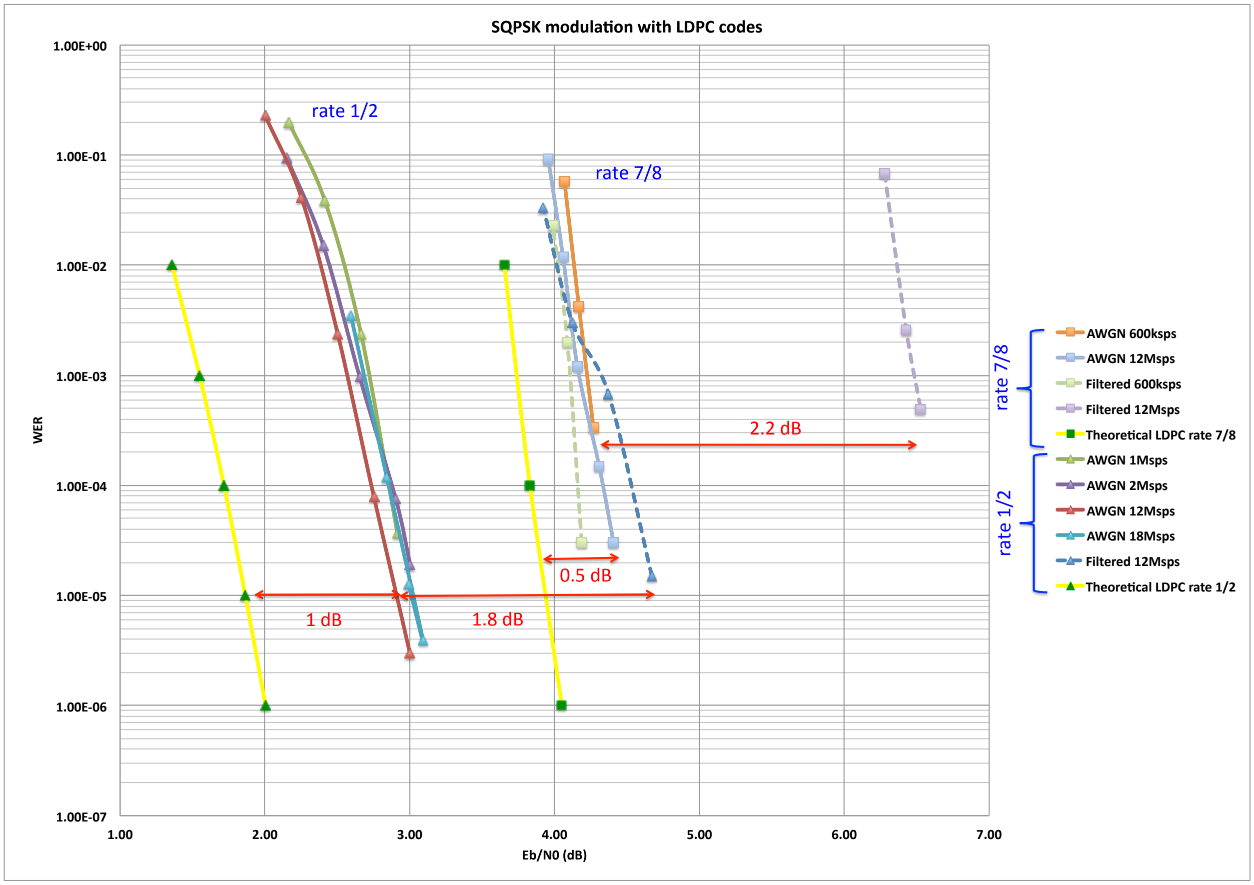

Figure 5. NB modem performance in DG2 Mode using LDPC codes. The curves for the rate ½ LDPC code are denoted by triangles. The curves for the rate 7/8 LDPC code are denoted by squares. Solid curves are the performance measured on the AWGN channel. Dashed curves are the performance measured on the emulated TDRS channel.

V. NB Modem Performance Data – TDRS Measurements

End-to-end testing of the NB modem over the TDRS channel is affected by variables beyond our control such as weather, antenna-pointing accuracy, signal fluctuation, path loss, etc. These variables add error bars to our measurements and make collecting a smooth curve, which could be done in a controlled lab environment, a difficult task. Moreover, the airtime for testing over TDRS was limited. For all of these reasons, we only collected 1 to 2 data points in the waterfall region of the error rate curve. We estimate the error bar for each data point to be approximately +/- 0.3 dB but we did not include the error bars in our plots to avoid cluttering the figures. We compared the TDRS data points to the AWGN curve and the distortion filter curve measured in the lab to confirm that the NB modem performance over the actual TDRS channel agreed with lab data. And therefore, we could use lab measurements to predict the NB modem performance over the TDRS channel allowing us to evaluate extensively the NB modem without requiring end-to-end TDRS testing for every scenario. We did not conduct any error floor checking using TDRS since doing would have required a run of multiple hours. We leave collecting errors at the very low error rates as additional modem exercises that could be done in the lab.

A. Spread Spectrum SQPN Modulation with LDPC Codes

For the SQPN modulation and the rate ½ LDPC code, we measured the decoding performance of the NB modem at three different data rates: 72ksps, 384ksps, and 600ksps. The WER measurements are denoted by large triangles in Figure 6. The data points are sandwiched between the AWGN curve and the distortion filter curve collected with the modem in the lab. The two higher data rate measurements followed the AWGN curve extremely well, indicating that the actual TDRS channel is much more forgiving than the channel emulated by the distortion filter. The 72ksps data showed an additional 0.3 dB implementation loss compared to the other two data rates, and this difference is within the uncertainty present in measurements due to environmental variables discussed earlier.

For the rate 7/8 LDPC code, we measured the modem decoding performance at 600ksps and plotted the data as blue squares in Figure 6. The data points are also sandwiched between AWGN curve and the distortion filter curve measured in the lab. The TDRS data tracks the AWGN curve well again, indicating that the impact of TDRS distortions on low data rate communication is small even in spread spectrum mode. The gaps between the modem performance over TDRS and the theoretical performance is about 1.5 dB for the rate ½ LDPC code and about 1 dB for the rate 7/8 LDPC code, confirming that the NB modem can attain the benefits of these new codes on the TDRS channel.

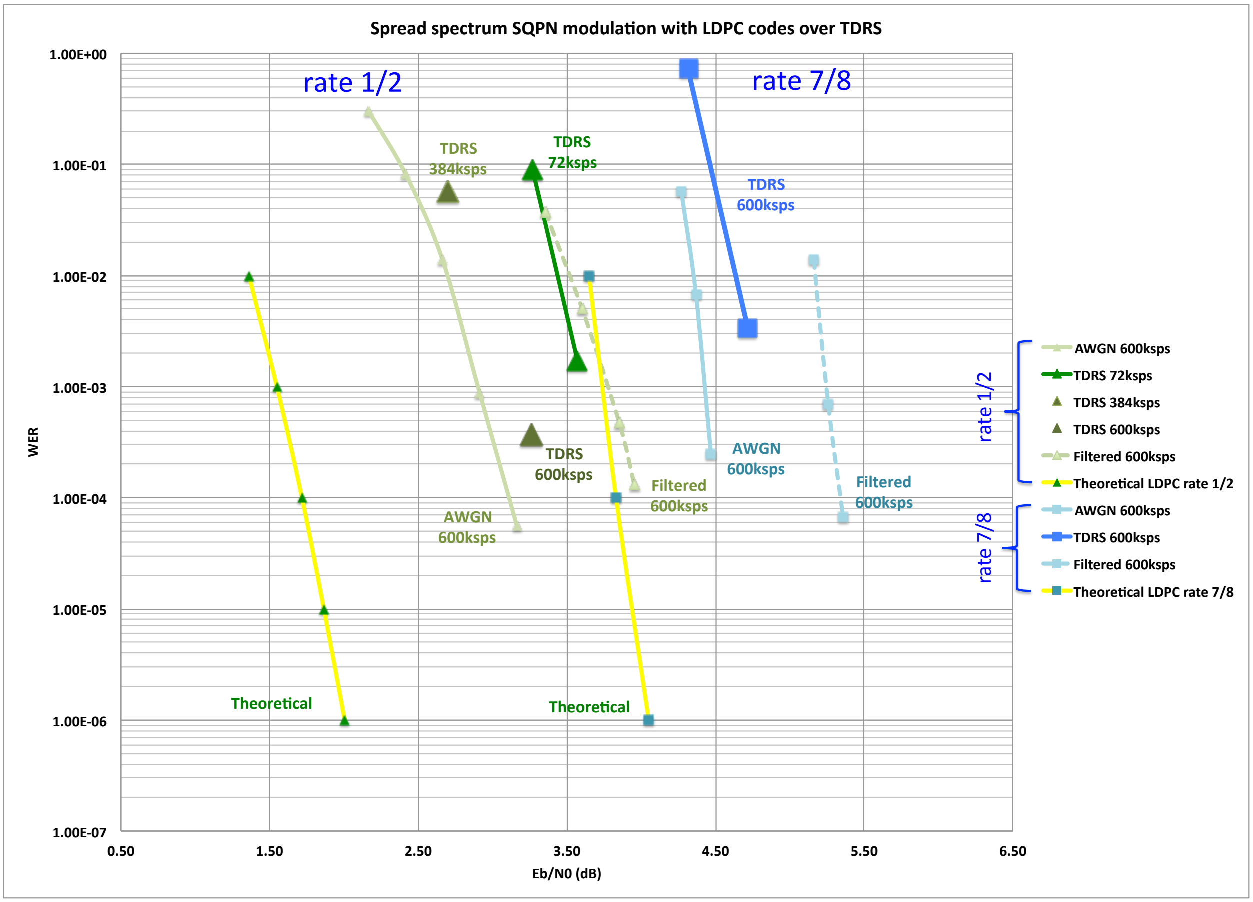

Figure 6. NB modem performance over a TDRS in DG1M2 using SQPN modulation with LDPC codes.

B. SQPSK Modulation with LDPC Codes

For the SQPSK modulation with the rate ½ LDPC code, we conducted end-to-end testing in 3 data rates: 1Msps, 12Msps, and 18Msps. Testing for the first two data rates took place during thunderstorms, affecting our measurements because the downlink carrier power fluctuated dramatically. We do not present data taken during bad weather in this paper. We tried again the following day when the weather was calm and collected data for the 18Msps case. We plot the WER data with large triangles in Figure 7. The modem performance at this high data rate was affected by TDRS bandlimiting. The additional degradation when compared to the AWGN curve is approximately 1 dB at a WER of 1e-4. We see that the slope of the measured word error rate curve is shallower than the AWGN curve. We are still investigating the cause of this modem behavior. One possible explanation is that the modem incorrectly reported codeword errors when there were none because the slope of the BER curve (shown in dotted-line with triangles) seems to track the slope of the AWGN curve well.

Even at this high data rate, the modem performance curve is closer to the AWGN curve than to the curve with the channel filter (measured at 12Msps), again suggesting that the TDRS emulation filter includes parameters with worst case values that are not usually found in a TDRS channel.

For the rate 7/8 LDPC code, we collected data at 12Msps and the result is plotted as blue-squares in Figure 7. The curve is again sandwiched between the AWGN curve and the curve with the TDRS channel filter measured in the lab. At a lower data rate, TDRS bandlimiting had a smaller impact on performance and the performance gap from the AWGN curve at a WER of 3e-4 is only about 0.5 dB.

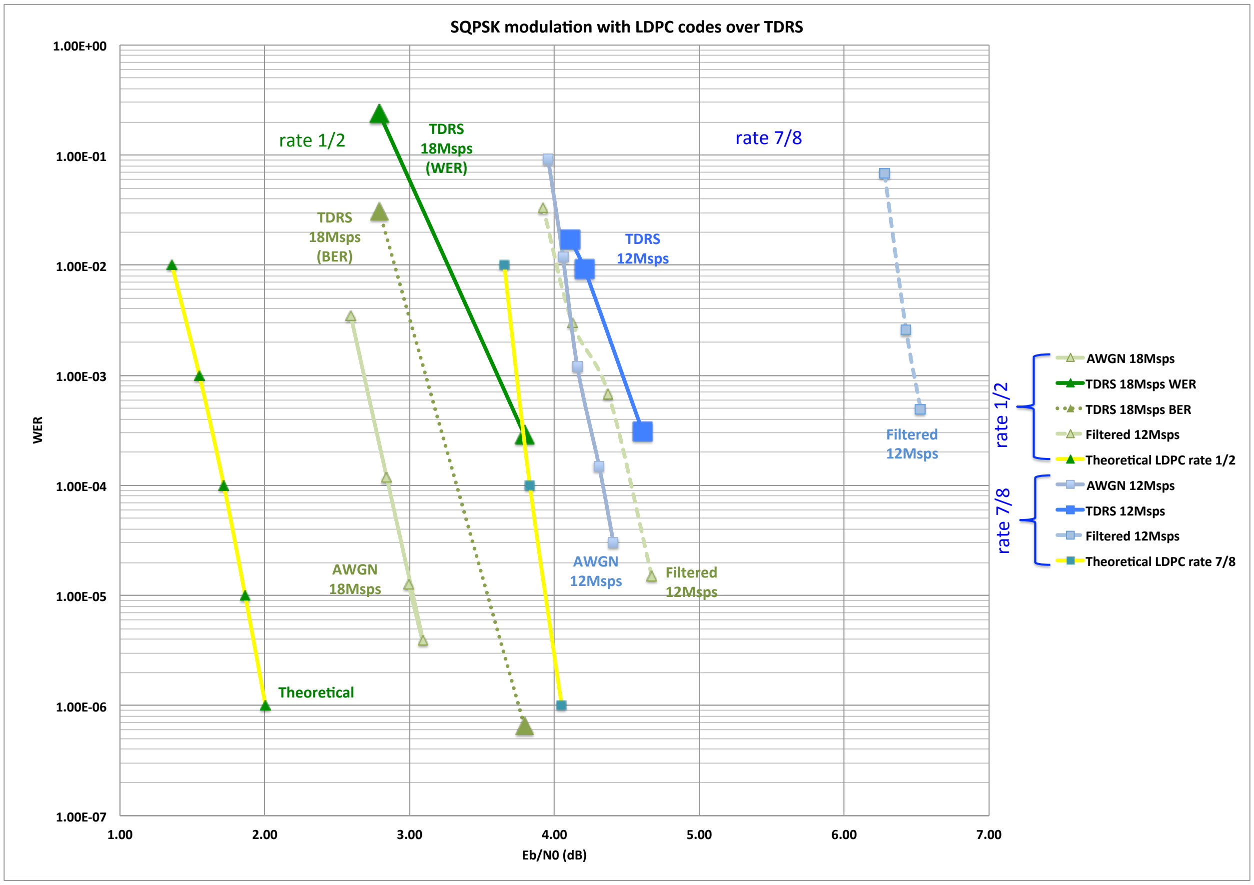

Figure 7. NB modem performance over a TDRS in DG2 Mode using SQPSK modulation with LDPC codes.

C. 8PSK Modulation with LDPC Codes

We measured the NB modem performance with 8-PSK modulation and LDPC codes at very high data rates in the lab. Results are plotted in Figure 8. Performance for the rate ½ code is denoted by triangles. We see that the measured AWGN curve has a shallower slope than the theoretical performance curve. This behavior is similar to the case with SQPSK modulation as discussed in the previous section and could be caused by the NB modem reporting incorrect codeword errors when there were none, because the BER curve (also shown in Figure 8) does not exhibit this behavior and has a slope that closely tracks the slope of the theoretical performance curve. The modem implementation loss in this case is about 1.5 dB.

Data for the rate 7/8 code are given as blue squares. The AWGN curve has a steep waterfall just like the theoretical performance curve and the modem implementation loss is approximately 1 dB. We attempted to collect data for this case over TDRS but there was not enough carrier power available during this test window to allow the data rate to go above 500kbps. At this data rate, the measured performance over TDRS was not affected by bandpass filtering and came very close to the AWGN performance.

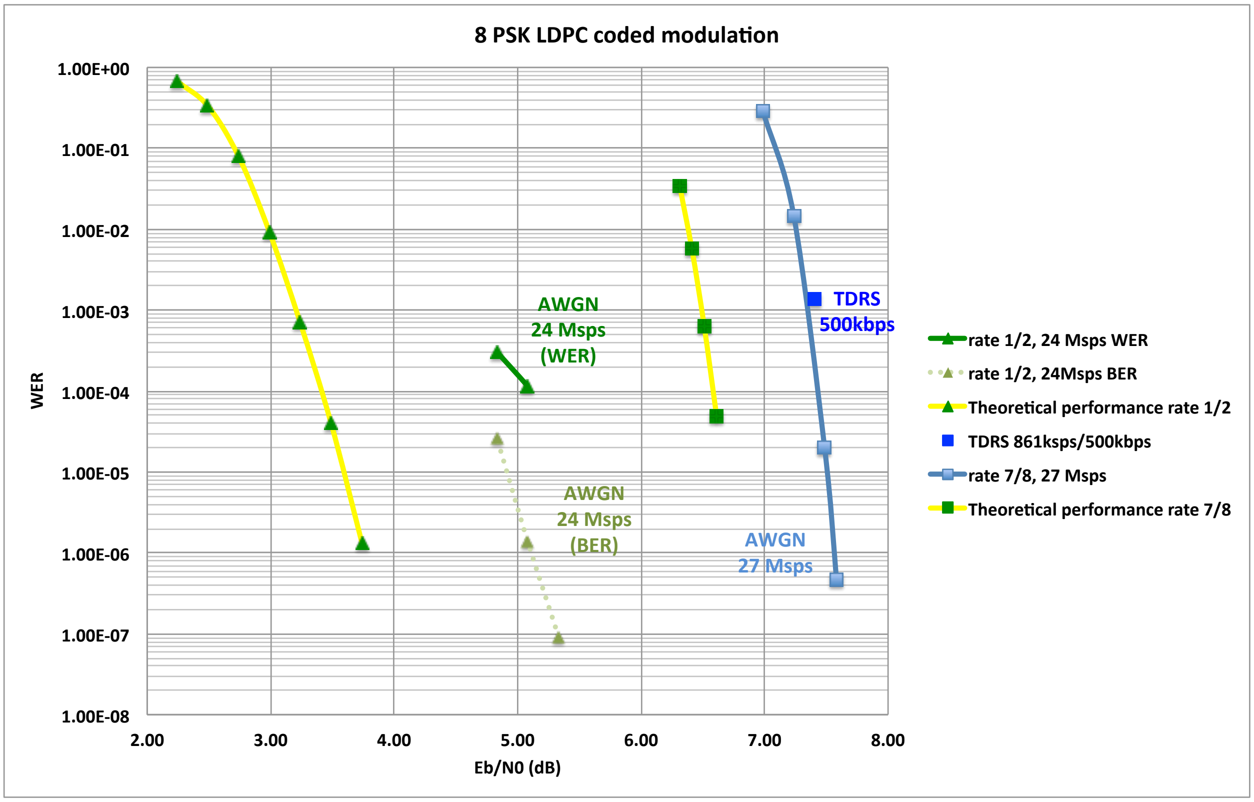

Figure 8. NB modem performance with 8-PSK modulation and LDPC codes.

VI. Summary

In this work, we measured the performance of USS CR NB modem qualification model both in a controlled laboratory environment and over the TDRS SSAR channel. Our findings are:

- The TDRS channel data points were located between the AWGN and distortion filter performance curves.
- The modem exhibited a larger implementation loss
    - in spread spectrum modes than in direct PSK modes
    - with the rate ½ LDPC code than with the rate 7/8 LDPC code
    - as data rate reduced in spread spectrum modes.

We summarize the modem performance on the TDRSS SSAR channel in Table 3. In spread spectrum mode, the gap from theoretical performance for the rate ½ code was 1.5 dB at 384ksps and 600ksps, and 2 dB at 72ksps. The gap for the rate 7/8 code was 1 dB at 600ksps. In SQPSK mode, the gap for the rate ½ code was 2.2 dB at 18Msps and the gap for the rate 7/8 code was 0.8 dB at 12Msps. The impact of the TDRS bandlimiting channel was evidenced by the larger gap measured in the high data rate 18Msps case.

Data Group and Modulation	LDPC Code Rate	Data Rate (sps)	WER	Gap between TDRSS data point and Theoretical Performance
DG1M2 Spread Spectrum SQPN	1/2	72k	1.71e-3	2 dB
		384k	5.75e-2	1.5 dB
		600k	3.75e-4	1.5 dB
	7/8	600k	3.33e-3	1 dB
DG2 SQPSK	1/2	18M	2.9e-4	2.2 dB
	7/8	12M	3.1e-4	0.8 dB

Table 3. Combined receiver and decoder implementation loss measured on the TDRS channel.

The TDRS channel emulation filter was designed to model the 3 dB bandwidth, gain flatness, gain slope, and phase nonlinearity that characterize a worst case TDRS SSAR channel, but the filter does not include all distortions that could be present in customer equipment. The channel observed in testing did not exhibit the worst case passband simulated by the TDRS channel filter but did contain distortions that were not modeled by the filter. The end-to-end test system did not include severe nonlinearities, for example AM/AM and AM/PM that are allowed by customer platforms. Depending on the customer equipment, the new coded modulation schemes could perform as well as the TDRS data points or could exhibit an implementation loss closer to or even higher than the distortion filter measurements. NASA has accounted for all of the above when specifying the modem requirements[7].

VII. Future Work

Results from HMD and TDRS testing of the USS CR NB modem in non-legacy modes have demonstrated the maturity of the new coded modulation schemes as implemented by the new modem. However, the efforts to make the new modem ready for operation continue beyond these tests. The NB modem uses a fixed iteration decoder, but a variable iteration decoder could improve the decoding performance by allotting more decoding iterations to "noisier" received words that might require more decoding iterations to converge. The frame synchronizer could be improved to always pick the best starting symbol offset and thereby dynamically adjust to various operating conditions. Performance in low signal-to-noise ratio regions could be improved by optimizing various loop bandwidth settings without giving up the ability to track spacecraft dynamics. An external decoder can be interfaced with the new modem through the soft symbol combining port and other CCSDS coded modulation combinations can be evaluated for future missions. Performance of 8-PSK coded modulations at high data rates (e.g. 27 Msps) over the TDRS channel could be measured. These tasks will help ready the USS CR modem for supporting the next generation of NASA missions.

Appendix A

Specifications for the TDRS Channel Emulation Filter

Center Frequency	370 MHz
Passband Gain Slope (366.5 MHz to 373.5 MHz)	0.8 dBc
Bandwidth (3dB)	365 MHz to 375 MHz
Phase Non-Linearity (3dB BW)	13.1 deg

Acknowledgments

The authors would like to thank the engineering staff at NASA WSC, especially Jim Gorghuber, David Cunniff, James Henry, Winslow Joy, and Jack Osborn for their support of our modem testing at the HMD and over TDRS.

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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