SCaN Network Ground Station Receiver Performance for Future Service Support

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The National Aeronautics and Space Administration (NASA) Space Communications and Navigation (SCaN) network consists of the Space Network (SN), the Near Earth Network (NEN), and the Deep Space Network (DSN). Historically, the three NASA networks have used different ground station telemetry receivers since these networks serve different applications and have different service requirements. In order to support the demands of future missions, SCaN has developed plans to support advanced modulation and coding techniques, including Low Density Parity Check (LDPC) codes. This paper presents the measured performance comparison of selected current and future ground station receivers within the SCaN network using LDPC rate ½ short length code. These receivers include the SN Integrated Receiver, the DSN Downlink Telemetry and Tracking (DTT) receiver, and the commercial-off-the-shelf (COTS) User Services Subsystem (USS) Component Replacement (CR) Narrowband Modem prototype receiver. Some of these receivers were not designed for use in the LDPC low E_s/N_o operating region, but our results show that with proper receiver loop bandwidth optimization and configuration, all of these receivers are capable of providing good performance with this code.

I. Introduction

In 2008, NASA's three Communication and Navigation networks, the Space Network (SN), the Near Earth Network (NEN) and the Deep Space Network (DSN), were gathered under the Space Communication and Navigation (SCaN) Program in order to provide integrated space communications, navigation, and data system services to NASA and external organization missions and to ensure that the networks could meet the evolving and diverse needs of future flight missions[1]. This agreement gave further impetus to the system engineering task already underway to determine current and future services that could be offered by all three networks with low infrastructure and operations cost[2]. Historically the three networks were designed and developed to support different mission requirements and hence have been implemented using specialized ground station systems. In particular, the ground station receivers supporting telemetry and navigation observables have been designed to support telemetry and ranging signal structures that meet the mission requirements particular to their primary mission customers. As SCaN seeks to offer more common and new services across its constituent networks and determine the future system level requirements for its three networks[3], it has become important to determine if the existing ground station systems will be able to accommodate the desired systems and examine how to develop low cost yet flexible equipment that can meet the evolving requirements on the SCaN network.

This paper uses the existing SN Integrated Receiver (IR), the DSN Downlink Telemetry and Tracking (DTT) receiver, and an early commercial-off-the-shelf (COTS) prototype of the User Services Subsystem Component Replacement (USS CR) narrow band receiver as examples to discuss the general issues of adapting ground station subsystems for support of future services. The USS CR receiver will be used to replace specific SN narrow band receivers at the White Sands Complex. The performance of the production version of the USS CR modems is detailed in several SpaceOps 2012 papers[4,5]. The new Low Density Parity Check (LDPC) code specified for support in the SCaN System Requirement Document[3] is taken as a test case. We focus on the performance of these three

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receivers for reception of a telemetry signal using the r=1/2, short block length (k= 1024) code. The paper details why the existing receivers are able to support this specific LDPC code, how the commercial receiver was modified in order to be able to support them, and concludes with some general comments on receiver design to enable low-cost receiver evolution and reuse to meet future SCaN and mission requirements.

II. Description of LDPC Codes and Impact on Receiver

Figure 1 shows the simulated performance of current rate ½ codes. Variant of all these codes, except LDPC, are currently used in one or more of the SCaN networks at this time. The LDPC rate 1/2 (n=2048, k= 1024) is being implemented by the USS CR Project and will become operational in specific single access users in the near future. (Note that the figure below gives the performance of LDPC r = ½ (n=32768, k = 16384) which is ~1 dB better than the n=2048, k=1024 code). This figure highlights the remarkable behavior of these codes: they have near-capacity performance and are less prone to error floors than other high performance codes, such as turbo codes. Most importantly, they can be implemented using much simpler and faster decoders and hence are amenable to both ground and flight realizations.

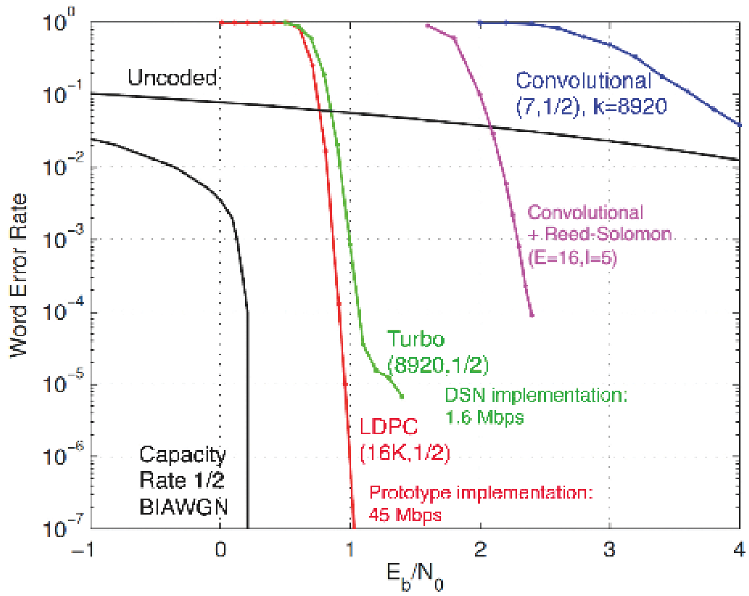

Figure 1. Theoretical performance of current rate ½ codes
(Courtesy Kenneth Andrews, JPL)

The Consultative Committee for Space Data Systems (CCSDS) has standardized a family of LDPC codes for use by future SCaN and international missions[6]. Code rates vary from 1/2, 2/3, 4/5 to 7/8, and are specified with permitted code lengths from 1024 to16384. The longer codes (higher code length or k) require lower Signal-to-Noise Ratio (SNR) and have steeper performance (i.e., achieve their optimum implementation loss with respect to ideal) than shorter codes. Higher code rates require less bandwidth. It is anticipated that the Deep Space missions will utilize these codes to obtain low power performance at high data rates where turbo decoding is more difficult. Near-Earth missions using the SN have requested use of the LDPC rate ½, k = 1024 code for applications requiring power and bandwidth efficiency and those using the NEN for high data rate applications will likely find the higher rate LDPC codes useful with limited bandwidth allocation at their downlink frequency.

Figure 2 shows the BPSK/QPSK performance of the LDPC rate ½, k=1024 code on the Additive White Gaussian Noise (AWGN) channel along with two codes currently used by SN supported missions, the Convolutional k=7, r=1/2 Code (CC) and the concatenated Reed Solomon and Convolutional Code (RSCC)[7]. The SNR decoding threshold of this LDPC code is approximately 2.2 dB. Once the system SNR exceeds this threshold, the BER approaches zero rapidly. The SN offers the CC service at a BER of 1e-5. At this BER point, the LDPC code offers a potential 2.4 dB power savings over CC. Even when comparing to the concatenated RSCC, the LDPC code still has a 1 dB power advantage. Although the LDPC decoder is more complex than the CC and RSCC decoders, the complexity can easily handled by modern computer processors.

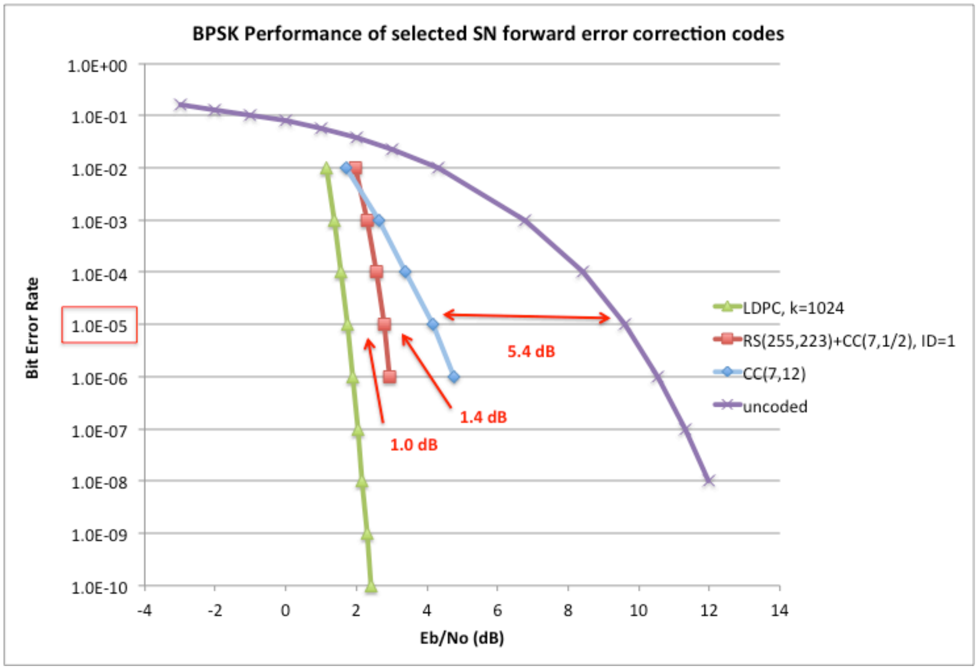

Figure 2. Performance of selected SN supported coding schemes

III. Existing SCaN DSN and SN Narrow Band Receivers

As mentioned above, the DSN Downlink Telemetry and Tracking (DTT) receiver and the SN Integrated Receiver (IR) are the receivers currently in use by DSN and SN networks. The receiver at the core of the DTT is the Block V Receiver[8]. It was designed at JPL over several years in the late 1980's and became operational in the early 1990's.[9,10] In the ensuing years, receiver boards have been redesigned to take advantage of high speed electronics and to add support for new decoders, but the performance of the receiver has not changed. As it has been designed for reception and tracking of very weak signals, its performance can be optimized given the modulation and telemetry signal format and data rate expected. The DSN supports residual carrier BPSK modulation for data rates from 10 bps to 100Kbps, and direct modulation of the data signal using BPSK and QPSK modulations at data rates from 100Kbps to 6 Mbps. Ranging tones can be transmitted in the downlink signal as well if navigation products are needed. The DSN uses frequency predicts in order to aid acquisition and tracking of the spacecraft signal. In order to minimizing the receiver implementation loss while maintaining achieving the required time for acquisition and frequency residual tracking performance, Deep Space mission telecommunication engineers develop DTT configuration tables for their mission by providing look-up tables to be used to configure the DTT for each mission data rate. These tables specify the parameters used by the receiver's synchronization loops and depend on whether fully suppressed or residual carrier modulation is used and what subcarrier frequency is planned[11].

The Integrated Receiver is the narrow band receiver used by the SN to demodulate the signals transmitted from Low Earth Orbiting spacecraft via the Tracking and Data Relay Satellite (TDRS) to the TDRS Ground Stations[12]. Table 2 lists the Signal Service Access Return (SSAR) signaling formats supported by the TDRS System (TDRSS), spread or unspread signaling formats with suppressed carrier BPSK and SQPSK modulations are called Data Group 1 and Data Group 2, respectively.

Table 1 TDRSS SSAR service modes.

TDRS SSAR Data Rate Range	Data Group 1			Data Group 2
	Mode 1	Mode 2	Mode 3	
I channel	2 - 300 kbps	2 - 300 kbps	0.2 - 300 kbps	2 kbps-6 Mbps
Q channel	2 - 300 kbps	2 - 300 kbps	2 kbps - 6 Mbps	2 kbps-6 Mbps

Notes:
In DG1 Mode 1, each I and Q channel is spread with a long PN sequence – length 256 * 2^{10}-1.
In DG1 Mode 2, each I and Q channel is spread with a short PN sequence – length 2^{10}-1.
In DG1 Mode 3, the I channel is spread with the long PN sequence, and high data rates can be used directly (unspread) on the Q channel.

IV. Prototype USS CR Narrow Band Receiver

The prototype modem was derived from a COTS product. The initial version supported only the waveforms specified in the SN Users Guide (SNUG)[7]. The TDRS S-band Single Access Return (SSAR) service modes are listed in Table 1. Data Group 1 uses spread spectrum modulation for low data rate communications. Data Group 2 uses direct PSK modulations for medium to high data rate communications. The SN also offers convolutional code (CC) services, including the CCSDS defined code with rate ½ and constraint length of 7. Puncturing is used on the rate ½ CC to obtain a code with a higher code rate. The SNUG states a BER requirement of 1e-5 for the (7,1/2) CC service and the code provides a coding gain of approximately 5.4 dB over an uncoded system as seen in Figure 2. The (7,1/2) CC can be concatenated with an outer (255,223) Reed-Solomon (RS) code to increase the coding gain over CC by an additional 1.4 dB. The IR supports CC encoding and decoding, but does not have RSCC capabilities. Therefore, when missions using the SN wish to use RSCC coding, they have relied on the SN to provide the CC service via the IR and they have performed the RS encoding and decoding at their Mission Control. The LDPC rate ½, k=1024 code adds an additional 1 dB coding gain over the RSCC code. Because the slope of the LDPC decoding error rate curve is steeper than those of the current codes, the coding gain of the LDPC code over other codes in fact increases as the BER requirement is made more stringent.

For the (7,1/2) CC, the theoretical decoding threshold at the SNUG 1e-5 BER requirement is 4.18 dB Eb/No. The CC decoder in the legacy IR was only designed to work when the system Eb/No was higher than this threshold. The node sync implementation in the CC decoder was not optimized for operations below 4.18 dB. When the system is put into a lower regime, the CC decoder reinitialized its node sync often, leading to frequent polarity changes in the decoded bits and longer error bursts than the output of a working decoder. If an outer RS code were used, the frequent polarity changes and the longer error bursts would result in a high RS decoding error and a large implementation loss for the concatenated RSCC code. The DTT does not have this issue and can obtain the full coding gain of the concatenated RSCC.

Since the initial prototype modem was designed to meet the SNUG requirement, the modem could not maintain carrier lock at Eb/No much lower than 4.18 dB, which corresponds to Symbol SNR or Es/No of 1.18 dB for the rate ½ code. A modification request was issued to modify the COTS modem and lower the carrier tracking threshold down to -1.5 dB Es/No for both DG1 and DG2 modes. The modem also had to handle a +/-230 kHz Doppler and +/- 1.5 kHz/sec Doppler rate at the new threshold. Because the modem did not have an internal LDPC codec, demodulated soft symbols were routed out of the modem to interface with an external codec. The soft symbols were quantized to 7 bits in DG2 mode but were restricted to 3 bits in DG1 mode due the unbalanced data rate requirement in this mode and the limited number of available signal output pins.

With the carrier tracking issue solved, the modem also needed to acquire and track unknown symbol offsets at the low Es/No region. The prototype modem provides the flexibility to adjust its symbol acquisition and tracking loop bandwidth as a function of the system symbol rate. The allowed bandwidth setting ranged from hundreds of Hz to 100 kHz. Narrowing the loop bandwidth increases noise rejection but reduces the modem's ability to track Doppler originated by spacecraft motion. Modem measurements made for this paper used the narrowest loop bandwidth setting that produced the best decoding performance without accounting for Doppler effects.

With the aforementioned modifications and proper selection of loop bandwidth settings, the prototype modem was demonstrated to work with the LDPC rate ½, k=1024 code at its decoding threshold. The combined receiver and decoder implementation loss is discussed in Section VI.

V. Receiver Tracking Loops

Advanced modulation and coding techniques may place new requirements on the SCaN ground station receivers. In particular, power efficient codes such as LDPC require the receiver to operate at lower signal SNR and Es/No and this can result in additional requirements on the receiver tracking loop bandwidths. This section briefly addresses the available tracking loop bandwidth configuration that were used for all three receivers to enable operation with the LDPC rate ½, k= 1024 code.

The IR tracking loops were designed to operate at E_s/N_o levels above 0 dB in order to accommodate the design requirement of supporting the convolutional rate ½ code. This code requires the symbol tracking loop to operate at an E_s/N_o of 1.5 dB, equivalent to an E_b/N_o = 4.2 dB, for a decoded bit error rate of 10^{-5}. However to support the LDPC rate ½, k= 1024 code, the receiver would need to track the signal down to at least -1.26 dB E_s/N_o (or an E_b/N_o of 1.74 dB) for a 10^{-5} BER. To enable tracking of the signal at lower E_s/N_o, the receiver synchronization loop bandwidths must be set to the lowest setting possible.

The IR was developed with four possible settings for the Jitter Bandwidth: "NONE", "0.01%", "0.1%", and "2%". Testing of the IR with the CCSDS LDPC r=1/2, k= 1024 codec was conducted at the Electronics Systems Test Laboratory (ESTL) at the Johnson Space Center (JSC) in 2007[13]. Initially, the IR Jitter Bandwidth setting was set to "NONE", which is the nominal selection and thus is schedulable. Symbol slips occurred frequently at the low Eb/No region where the rate ½, k=1024 LDPC code offers the most coding gain over legacy coding schemes as shown in Figure 2. Use of an IR Jitter Bandwidth setting of "2%" resulted in a tighter loop bandwidth than with the "NONE" setting. Using the narrower symbol tracking loop bandwidth reduced the symbol slip rate and improved LDPC decoding performance at low Eb/No's achieving the benefit of the new code. The "2%" setting was initially designed for use by the Space Shuttle for specific rates and formats, most often for Shuttle tape recorder playbacks, and is no longer used operationally. However, the IR can still be manually configured in this mode and this results in narrow receiver symbol tracking loop bandwidths. The measured loop bandwidth settings are summarized in Table 2[13].

Table 2 Measured IR Loop Bandwidths

	IR Loop Bandwidth (Hz, % of Symbol Rate)	
Information Rate / Symbol Rate (r=1/2 code)	**IR Jitter Bandwidth setting "NONE"**	**IR Jitter Bandwidth setting "2%"**
24 Kbps / 48 Ksps	38 Hz, 0.08%	~7 Hz, 0.014%
1 Mbps / 2 Msps	2.6 KHz, 0.13%	275 Hz, 0.014%

On the other hand, the DSN DTT was originally designed to support rate 1/6, constraint length 15 convolutional codes and eventually rate 1/6 Turbo codes. Therefore the DTT Functional Requirements[8] specify that the receiver must be able to track down to an Es/No of -8 dB, which is far lower than the LDPC rate ½ threshold. As a result of the -8 dB Es/No tracking requirement, the DTT was implemented to provide very narrow carrier and symbol synchronization loop bandwidths. The DTT carrier loop bandwidth can be set below 0.5 Hz and up to 200 Hz, while the symbol loop bandwidth can be set below 10 mHz and up to 25 Hz. Narrower carrier and symbol loop bandwidths are not practical for normal mission operations, due to factors such as uncompensated Doppler, transmitter phase noise, solar scintillation, and bit jitter that may cause the tracking loop to drop lock if the bandwidth is too narrow. The use of narrow loop bandwidth in the tracking loops is made possible by the removal of Doppler using accurate frequency predicts. However when accurate frequency predicts are not available (e.g., during initial acquisition of spacecraft telemetry following launch), the DSN often needs to use a secondary receiver with wider tracking loop bandwidth capability to assist with signal acquisition. This is a disadvantage compared to the IR, which was designed to track spacecraft with large amounts of uncompensated Doppler and is used for initial acquisition as well as nominal operations.

As discussed in Section IV, modifications were made to the early COTS prototype of the SN USS CR modem in order to enable tracking at E_s/N_o below 0 dB as well as tracking of high spacecraft dynamics.

VI. Receiver Performance

The implementation losses of three different SCaN receivers using CCSDS LDPC rate ½, n=2048, k=1024 code were compiled for this paper from various measurements in labs at JPL and at the ESTL at JSC. Two of the receivers considered, the DSN Downlink Telemetry and Tracking (DTT) receiver and the SN Integrated Receiver (IR), are currently integrated as part of the SCaN network, while the third receiver was an early COTS prototype of the SCaN USS CR modem. While receiver implementation loss is generally a complex function of many different variables, all three receivers showed an implementation loss dependence on data rate. A JPL-developed external LDPC decoder was connected to the soft-decision outputs of the receiver to provide end-to-end performance measurements, since none of the receivers considered had a built-in capability to perform LDPC decoding at the time of the measurements.

The external LDPC decoder, shown in Figure 3, was implemented on a Lattice FPGA as part of the SCaN baseband emulator[14]. The baseband emulator included an LDPC encoder and decoder module as well as an SNR estimator and frame synchronizer. The emulator unit was developed as part of an effort to verify performance of the protocol stack chosen by NASA's Human Exploration Program prior to full implementation within the SCaN network. It was used to ensure interoperability within the stack as well as offering early risk-reduction testing between flight and ground communications and data subsystems.

Figure 3. SCaN Baseband Emulator and LDPC Codec

Each of the SCaN receivers had a different scaling and number of quantization bits for the receiver soft decision outputs. The LDPC decoder performance depends on the scaling and quantization of its soft decision inputs. The ideal scaling factor for the soft decisions in an AWGN channel is $2A/\sigma^2$, where A is the signal amplitude and σ^2 is the noise variance. The LDPC decoder contains an estimator that is used to determine noise variance and the correct scaling factor, but cannot entirely recover losses due to receiver quantization or incorrect scaling of the soft decisions. The effect of estimation error on decoding performance depends on the magnitude and direction of the estimation error. The need for estimating the scaling factor could also be avoided entirely by taking a small performance penalty[18]. Each SCaN receiver also had a different physical interface for the soft decision outputs, which necessitated the building of a custom interface board to the LDPC decoder for each receiver.

The IR provided 5-bit soft decisions from the SSA Combining Output port, which was typically used for arraying purposes and not for external decoding. The scaling of the IR soft decision outputs was only roughly controllable by adjusting the Reference C/No parameter in 1 dB steps. The performance of the LDPC decoder with the IR was measured as a function of the Reference C/No parameter[13]. The DTT had 8-bit soft decision outputs that were taken from a connector between the demodulator and the Telemetry Processor (TLP), which normally performs convolutional, Reed-Solomon, and turbo decoding functions for the DSN. The scaling of the DTT soft decision outputs was automatically controlled by the built-in receiver symbol SNR estimator, based on the Split Symbol Moment Estimator algorithm. The early USS CR prototype provided 7-bit soft decisions; soft decision scaling was set manually inside the GUI. For the test results shown below, the scaling factor was set to ¼.

To allow for a valid comparison across receivers, the results shown in the following subsections are all using the CCSDS LDPC rate ½ (n=2048, k=1024) code and SQPSK modulation in an AWGN channel. SQPSK is a common modulation format used by many missions and supported by all three networks within SCaN for certain ranges in data rates. In order to compare receiver implementation loss over a wide range of data rates, data was taken using the modulations supported by each network at low data rates, SQPN for the SN and subcarrier modulations for the DSN. Furthermore, all FER results were collected with the SCaN baseband emulator as the external LDPC decoder to avoid data dependence on decoder implementation. The data was collected from a time period spanning 2007 to mid-2011. The implementation loss was measured at a frame error rate (FER) of 1×10^{-4} with respect to the theoretical FER curves provided in the CCSDS Blue Book[6].

A conceptual block diagram of the test setup for the LDPC FER measurements is shown in Figure 4. The LDPC encoder supplied an encoded symbol stream and a symbol clock to the test modulator. The test modulator then modulated the IF carrier with the LDPC encoded symbols using SQPSK. Diverse test modulators were used for the three cases. For the DTT tests, the test modulator was a Rhode & Schwarz vector signal generator. For the IR tests, the test modulator was the Space Network's Test Modem. For the prototype USS CR tests, the internal test modulator of the USS CR modem was utilized. AWGN was added to the IF signal to create the desired Eb/No for each FER point. The receiver demodulated the noisy signal and produced soft decision outputs to the custom interface board. This board performed the signal level and format conversions necessary for the LDPC decoder input. A Labview GUI was created to control the LDPC encoder and decoder, and to display the measured frame error rate.

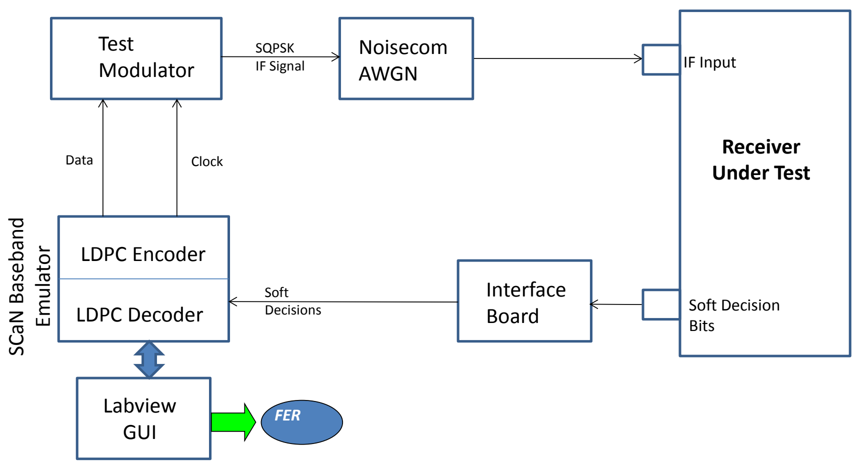

Figure 4. LDPC FER Measurement Block Diagram

A. DTT Implementation Loss Results

The DTT implementation loss with LDPC rate ½ coding and SQPSK modulation is shown in Figure 5 as a function of data rate. For bit rates below 10 kbps, the results show that the receiver implementation loss increases quite rapidly and confirms that SQPSK should not be used with the DTT at these low data rates. At low data rates and low Es/No associated with the LDPC decoding threshold, the squaring loss of the Costas loop used for carrier tracking is quite high and induces significant radio losses. For comparison, a plot of the measured DTT implementation loss for the Kepler transponder with a subcarrier modulated signal is shown. Note that use of a residual carrier allowed for the bit rates down to 100 bps with an implementation loss of around 1 dB. Figure 2 illustrates the difficulty of using a fully suppressed carrier modulation like SQPSK at low data rates. In typical deep space operations with the DSN, SQPSK is only recommended for use when the symbol rate is greater than 40 ksps[16]. For these test results, the DTT symbol loop bandwidth setting ranged from 0.1% to 0.00005% of the symbol rate.

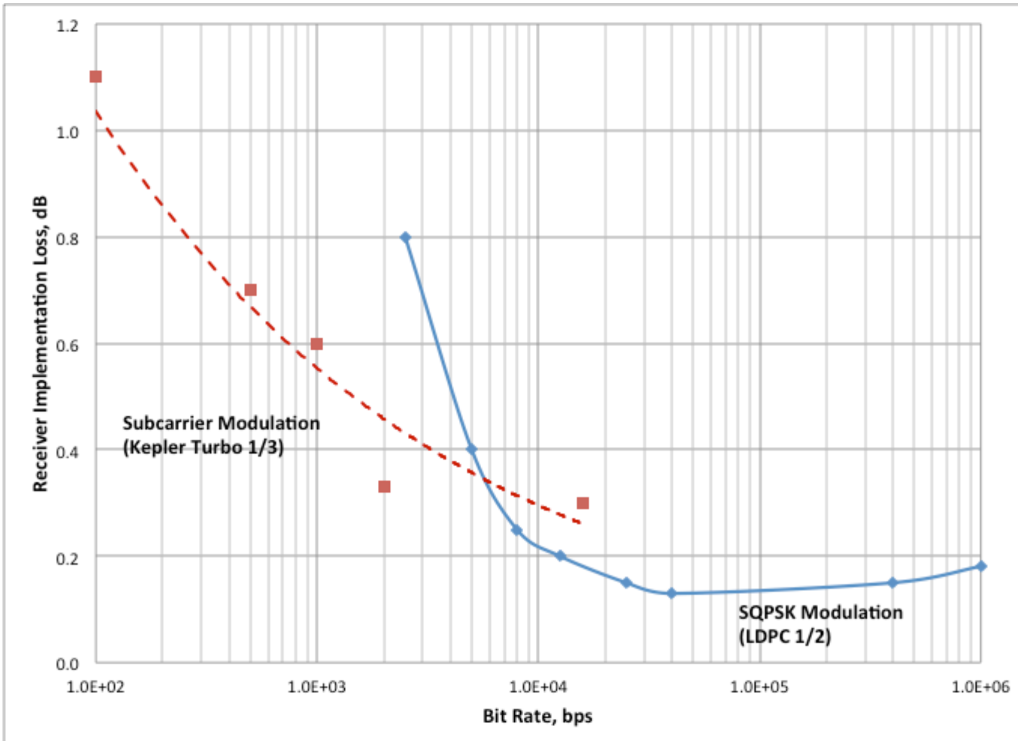

Figure 5. DSN Receiver Implementation Loss for SQPSK versus Data Rate (LDPC Rate ½ @ 1E-4 FER)

B. IR Implementation Loss Results

In order to operate the IR at E_s/N_o values near the LDPC threshold, the IR was configured in a non-standard mode with a "2% jitter" setting to provide the narrowest synchronization loop bandwidths and hence the best performance in AWGN with no Doppler[13]. Adjusting the jitter setting provided roughly a 10 dB increase in loop SNR which allowed for better FER performance at low Es/No in AWGN.

Figure 6 shows the implementation loss of the SN Integrated Receiver with LDPC rate ½ coding and SQPSK. The measurements were compiled from references[13,17], with the IR configured for SSA DG2 mode. Compared to the DTT results, the IR implementation loss with LDPC coding is slightly higher overall. This is in part to due to the fewer number of soft decision quantization bits from the IR, as well as the imperfect soft decision scaling through the Reference C/No parameter. There is also more variability in the measured IR implementation loss with respect to data rate; however, the trend still shows an inverse relationship between data rate and implementation loss for the IR. For symbol rates less than 600 ksps, the SN supports DG1 mode return links using SQPN modulation. The IR performance with the LDPC rate ½ and SQPN is also shown in Figure 6. The IR symbol loop bandwidth for these test results was approximately 0.014% of the symbol rate.

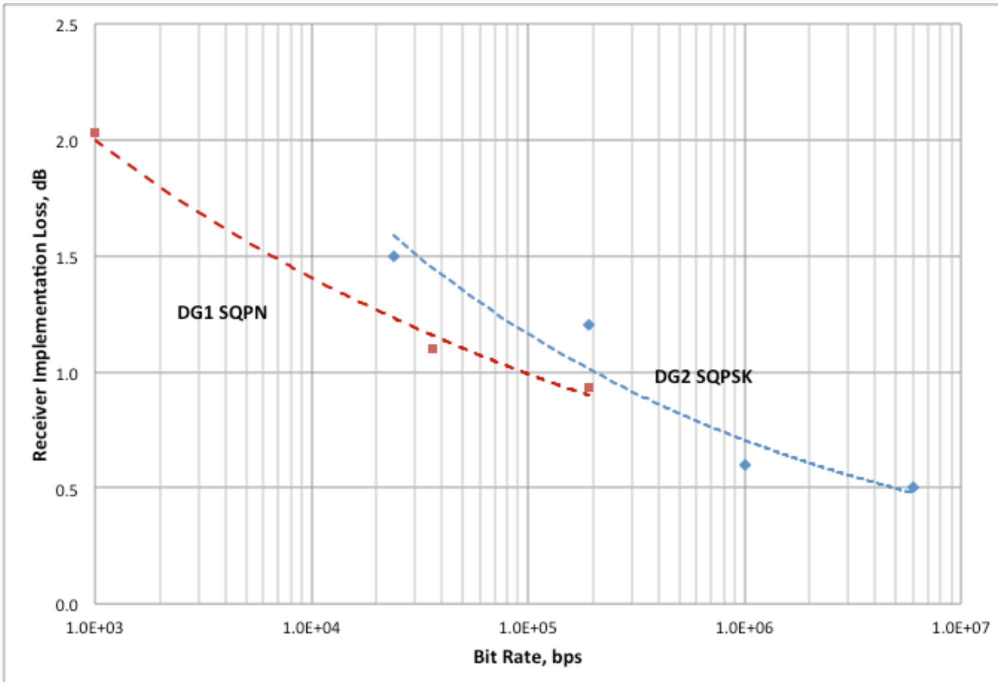

Figure 6. IR DG2 SQPSK Implementation Loss versus Data Rate (LDPC Rate ½ @ 1E-4 FER)

C. Early COTS USS CR Prototype Implementation Loss

The implementation loss of the early COTS USS CR prototype with the LDPC rate ½ decoder is shown in Figure 7. For DG2 SQPSK, the receiver was configured with a carrier loop bandwidth of 0.001% of the symbol rate, and a symbol loop bandwidth of 0.001% of the symbol rate. For DG2 SQPSK, the trend for the USS CR prototype also shows an inverse relationship between receiver implementation loss and data rate. While this is true in general, it should be noted that as the data rate increases to the upper limits of the receiver capability, the implementation loss is also expected to increase. For this early prototype, the upper limit was about 25 Mbps and no LDPC FER measurements were available in this data rate region.

Figure 7 also shows the USS CR prototype implementation loss for DG1 SQPN modulation with LDPC rate ½. The loss with SQPN does not show as much of a data rate dependency as with SQPSK, within the data rate region between 25 kbps and 300 kbps. With a rate ½ code, 300 kbps is the maximum bit rate in DG1 mode.

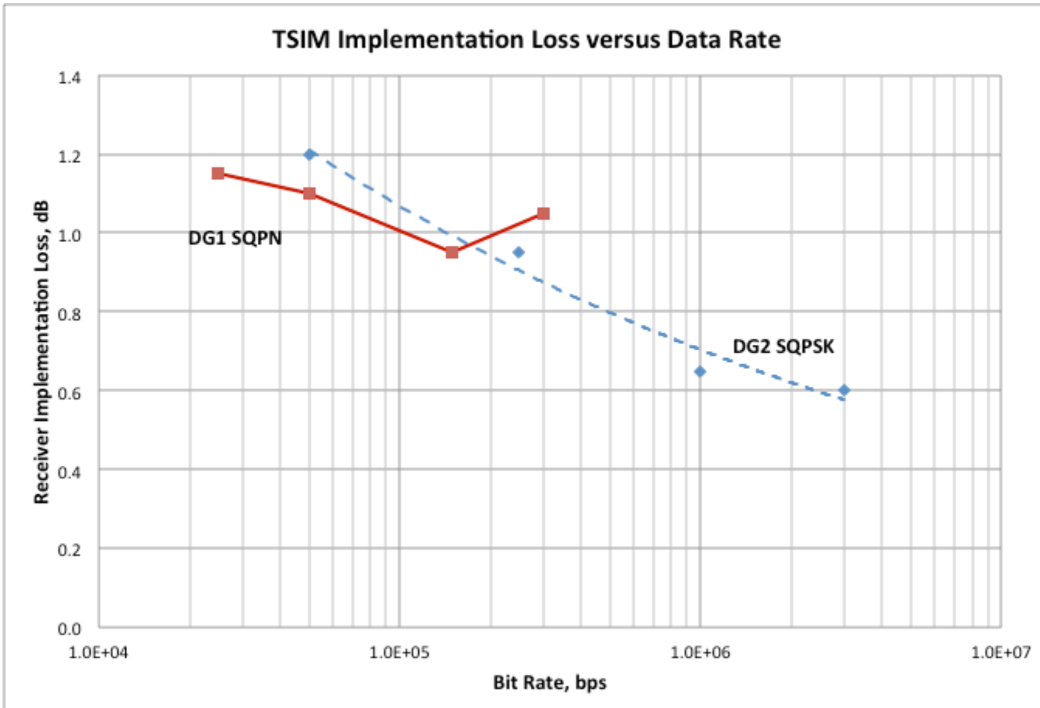

Figure 7. Early USS CR Prototype Implementation Loss for SQPSK versus Data Rate (LDPC @ 1E-4 FER)

D. Performance Comparison

A comparison of the FER performance of the three receivers in their nominal SQPSK data rate regions is shown in Figure 8. All the FER curves are shown for 1 Mbps data rate. It can be seen that all three receivers provide less than about 0.6 dB implementation loss with LDPC coding at these data rates. It should be noted that this is true despite the fact that the synchronization loops of the IR and the early COTS USS CR prototype were not originally designed to operate in the low Es/No regions (around -1 dB Es/No) associated with the LDPC decoder threshold. In the case of the DTT FER curve, the symbol loop bandwidth was set to 1 Hz, or 0.00005% of the 2 Msps symbol rate. This compares to 0.014% for the IR symbol loop bandwidth, and 0.001% for the USS CR prototype. At these high data rates it is not expected that the symbol loop bandwidth was a significant contributor to the difference in implementation loss, although larger symbol loop bandwidth do contribute to receiver implementation loss at lower data rates.

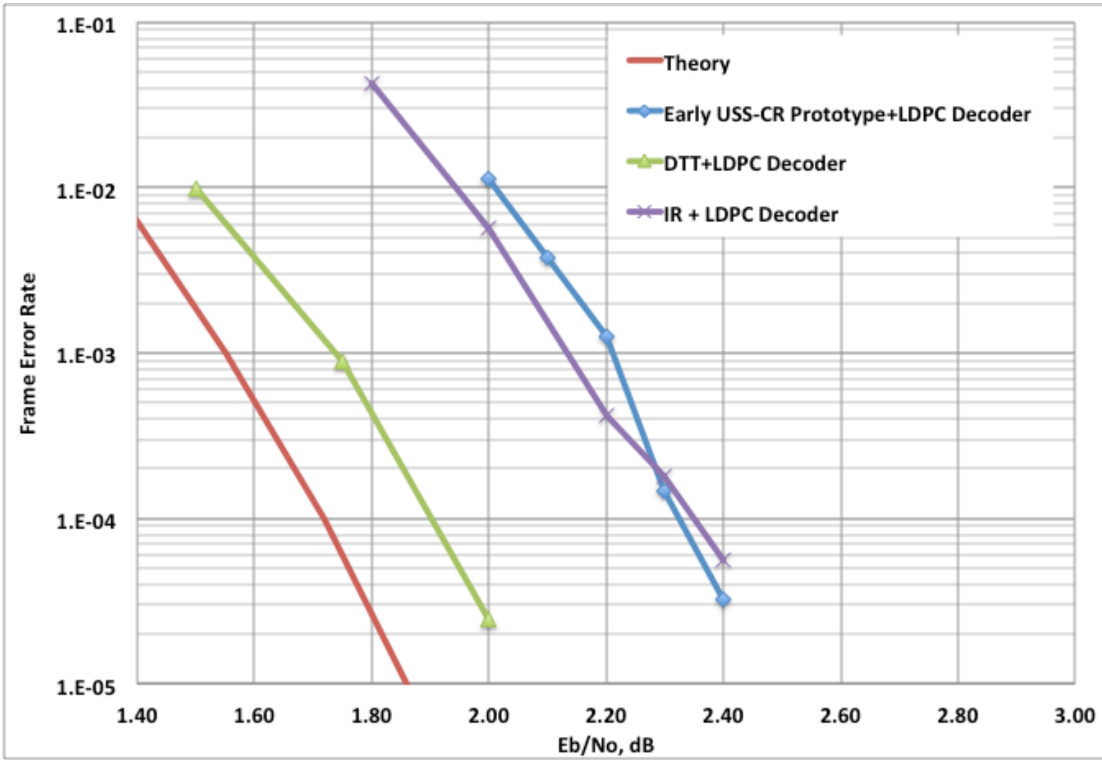

Figure 8. Receiver FER Comparison with LDPC (2048, 1024) Coding

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