Future Capabilities for the Deep Space Network

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ABSTRACT

Recently, the Deep Space Network (DSN) of NASA underwent a major upgrade (called the Network Simplification Project, or NSP) of its Telemetry, Tracking, and Command (TT&C) capability. As part of this upgrade, the ranging and telemetry equipment were redesigned and implemented in an architecture that allows easy addition of new capabilities.

This paper will look at three new capabilities that are in different stages of development. First, turbo decoding, which provides improved telemetry performance for data rates up to about 1 Mbps, will be discussed. The initial implementation of turbo decoding has recently been completed and will be used for the Messenger spacecraft. Next, pseudo-noise (PN) ranging will be presented. PN ranging has several advantages over the current sequential ranging, namely easier operations, improved performance, and the capability to be used in a regenerative implementation on a spacecraft. The PN ranging implementation has just begun; its first user will be the New Horizons mission. Finally, Low Density Parity Check (LDPC) decoding will be discussed. LDPC codes can provide performance that matches or slightly exceeds turbo codes, but are designed for use in the 10 Mbps range. LDPC research is still underway and the commitment for implementing into the DSN has yet to be made.

1.0 INTRODUCTION

Recently, the Deep Space Network (DSN) of NASA underwent a major upgrade (called the Network Simplification Project, or NSP) of its Telemetry, Tracking, and Command (TT&C) capability. As part of this upgrade, the ranging and telemetry equipment were redesigned and implemented in an architecture that allows easy addition of new capabilities. This was accomplished by moving many of the functions from discrete, custom built hardware, to general purpose commercial hardware and custom software.

Currently, there are three new capabilities that either have already been added, or are under consideration. After a review of the new TT&C system, we will look at these new capabilities. First, we will discuss turbo decoding, which provides improved telemetry performance for data rates up to about 1 Mbps. The initial implementation of turbo decoding has recently been completed and will be used for the Messenger spacecraft. Next, pseudo-noise (PN) ranging will be presented. PN ranging has several...
advantages over the current sequential ranging, namely easier operations, improved performance, and the capability to be used in a regenerative implementation on a spacecraft. The PN ranging implementation is just beginning; its first user will be the New Horizons mission. Finally, Low Density Parity Check (LDPC) decoding will be discussed. LDPC codes can provide performance that matches or slightly exceeds turbo codes, but are designed for use in the 10 Mbps range. LDPC research is still underway and the commitment for implementing into the DSN has yet to be made.

2.0 THE BASELINE TT&C EQUIPMENT

Recently, the TT&C equipment in the DSN has been upgraded by the Network Simplification Project (NSP) [1], [2], [3]. This upgrade resulted in a simplified system, with one controller for uplink equipment and one controller for downlink equipment. The uplink function consists of the uplink carrier generation, along with the generation and modulation of the two uplink data streams, command and ranging. The downlink consists of the receiver, which demodulates the telemetry and ranging signals, the correlation of the ranging signal and the decoding and synchronizing of the telemetry data.

Key to the ability to easily add new capabilities is how the ranging and telemetry upgrades were done. Previously, ranging was done using a custom, multiboard implementation, where the signal generation and correlation were done all in hardware. Addition of a new ranging modulation type would require considerable hardware modifications. However, the new implementation took advantage of the great increase in processing power provided by commercial Digital Signal Processors (DSP); all of the signal generation and correlation is done in software, running on the DSPs. That means that a new modulation type can be implemented by just an update to the software.

In the telemetry hardware, the old equipment, which was a chassis filled with custom boards, was replaced by a smaller VME chassis (called the Telemetry Processor, or TLP), with all of the current Consultative Committee for Space Data Systems (CCSDS) telemetry processing integrated onto one board and one single board computer. The implementation provides interfaces for additional boards to connect to the input symbol stream, which makes adding future decoders straight forward. The software interfaces are designed to allow separate tasks for new decoders, greatly simplifying the integration of a new decoder into the system.

In the sections that follow, we discuss three new capabilities that are either being implemented or being considered for implementation in the new TT&C equipment.
3.0 TURBO CODES

Until recently, the main method for error correcting encoding of the telemetry data was to use either a convolutional code, either alone or in conjunction with a Reed-Solomon block code (Cyclic Redundancy Codes, or CRC, are also used at the block level, but they only detect errors). However, a new class of codes, called turbo codes, have been approved by the CCSDS [4]. New missions (such as the MERCURY: Surface, Space ENvironment, GEochemistry and Ranging mission, or MESSENGER; the Solar-TERrestrial RELations Observatory mission, or STEREO; and Mars Reconnaissance Orbiter or MRO) are basing their missions on these new codes.

Turbo codes are block codes. That is, the encoding is done on one block of data at a time. A transfer frame is the basic block. As part of the transfer frame, the 16-bit Frame Error Control Field (FECF) at the end of the frame is required; the FECF is a Cyclic Redundancy Code (CRC). After the encoding is done, the frame synchronization marker is attached to the beginning of the block. This is different than the sequence for the current concatenated convolutional / Reed-Solomon encoding. In that case, the transfer frame is Reed-Solomon encoded (which is a block code), has the frame synchronization marker attached, and then is convolutionally encoded.

One question that might be asked is why move to turbo codes? The reason is their performance. The performance of a code can be judged by the ratio of the energy-per-bit to the noise spectral density $E_b/N_0$ needed to achieve a desired probability of error $P_e$; $P_e$ is also known as the Bit Error Rate (BER). The lower the $E_b/N_0$ required for a given $P_e$, the better the code's performance.

Figure 1 provides a comparison of the two standard codes currently used for deep space and the new turbo codes. The current codes are the constraint length 7, rate 1/2 convolutional code (denoted as the (7, 1/2) code), concatenated with the (255, 223) Reed-Solomon code, and the constraint length 15, rate 1/6 (15, 1/6) convolutional code, also concatenated with the (255, 223) Reed-Solomon code. The comparison is for a frame size of 8920 bits, which corresponds to a Reed-Solomon interleave factor of 5. As can be seen, for a BER of $10^{-6}$, the rate 1/6 turbo code provides approximately 0.8 dB improvement over the (15, 1/6) concatenated code, the rate 1/4 code provides 0.6 dB improvement, the rate 1/3 code provides 0.4 dB improvement and the rate 1/2 is 0.3 dB worse. Comparing the (7, 1/2) code with the turbo codes, we see improvements of 2.4 dB, 2.2 dB, 2.0 dB, and 1.3 dB for the rate 1/6, 1/4, 1/3, and 1/2, respectively. Additionally, as we will soon see, there is another big advantage to turbo codes: the decoder requires fewer computations than the (15, 1/6) convolutional decoder, which provides more options for implementation.

Turbo encoding of a data block uses two constraint length 4 convolutional codes, one that operates on the bits in their original order, and one that operates on the bits in a permuted or "interleaved" order. Turbo
decoding proceeds iteratively by alternately decoding the two component codes (non-interleaved and interleaved). At each iteration, each constituent decoder updates its soft decisions (the probabilities that each message bit is a binary '1') based on the structure of its convolutional code and the re-ordered soft decisions of the other decoder. Iterative decoding continues until the constituent decoders converge to a mutually satisfactory set of decisions, or until a fixed maximum number of iterations is reached. Details on the actual decoding process can be obtained from [5]; note that in addition to the actual decoding, the turbo decoder must handle functions such as frame synchronization (to determine the block boundaries), time tagging, pseudo derandomization, and CRC processing.

Since the decoder operates on blocks (frames), higher speed can be achieved by having multiple decoder elements. The total speed of the decoder is the product of the number of decoder elements and the average speed of an individual element. Only the frame synchronization process must operate at the input symbol rate; the decoder elements only must operate at the block rate divided by the number of elements available for decoding. This is the opposite of the previous codes – the convolutional decoder must operate at the symbol rate.

From [6], a turbo decoder implemented in a DSP is about a factor of 10 less complex than a (15, 1/6) convolutional decoder. What this means is it is simpler to build a turbo decoder than a decoder for the
(15, 1/6) code. This is what allows the turbo decoder to be implemented as software on commercial DSP boards, instead of the costly custom Application Specific Integrated Circuit (ASIC) implementation that was required for the MCD III, which is the (15, 1/6) decoder that is used in the DSN. In our case, we used VME boards with a total of eight Texas Instruments (TI) TMS320C6000 family DSPs available on a board.

Each DSP has a specific function: one is devoted to frame synchronization, one is for control and coordination, and the rest are for turbo decoding of the encoded frames. In the new NSP architecture, integrating the turbo decoder was straightforward. The DSP boards were added into the TLP chassis, the industry standard Front Panel Data Port (FPDP) interface was connected to the auxiliary decoder symbol stream interface, and the interface software was written. The decoded frames are passed over the VME backplane to the processor card that handles the data output. Additional DSP boards can be added easily – the encoded frames and the decoded bits are passed back and forth between the board with the frame synchronizer and controller and the additional board. This provides a speed increase by increasing the number of decoder elements that can operate in parallel.

Currently, a single DSP board has been integrated into the system, which supports the requirements for MESSENGER and STEREO. To support the requirements for MRO (1.6 Mbps), a second DSP board will be added before it launches in August of 2005.

4.0 PSEUDO-NOISE RANGING

Currently, all ranging for deep space by the DSN uses sequential square wave tones. However, there is another class of ranging modulation that has some advantages over sequential tones. This form of modulation is based on combinations of short pseudo-noise (PN) sequences [7], [8], [9].

Ranging is accomplished by modulating a ranging code onto the uplink carrier, demodulating and then remodulating it onto the downlink carrier by the spacecraft, then demodulating the downlink on the ground and correlating the received signal against what was transmitted. The correlation provides the time difference between the transmitted and received signals, and hence, the range to the spacecraft. The precision of the measurement is driven by the highest frequency of the ranging modulation (the higher the frequency, the more precise the measurement), and the ambiguity of the measurement is driven by the lowest frequency of the ranging modulation (the lower the frequency, the less ambiguous the measurement). Since ranging is normally performed when there is telemetry modulation on the downlink, the percentage of the total available downlink power that is devoted to ranging is relatively small, when compared to the power devoted to the telemetry (the ranging modulation index is much smaller than the modulation index of the telemetry); thus, to get a good measurement, the ranging signal must be integrated over a long time.
Sequential ranging accomplishes this by sending a series of square wave tones, each one a factor of two lower in frequency than the previous one; the highest frequency sets the precision and the lowest frequency sets the ambiguity. The advantage of this method is that only one tone is correlated at a time, and all the ranging power is in that one tone; both of these are major advantages when the hardware (the correlators) is the design limitation (due to capability or cost). The disadvantage with sequential ranging is that the reception on the ground can only start with the first tone, limiting when a measurement can start. To accomplish this, the receiving equipment must know when the cycle started on the uplink and must know to one second accuracy the round trip light time (RTLT) from the transmitting station to the spacecraft and back to the receiving station. For the weak signals that are typical for deep space ranging, it is not unheard of for the cycle time (the time for the ranging modulation to go through a complete set of the tones) to be on the order of 15 to 30 minutes. This limits when the data can be measured and can lead to inefficiencies in the tracking time (for example, if the downlink signal acquisition was delayed one minute past the time of the start of a ranging cycle, and the cycle time were 20 minutes, there would be a wait of 19 minutes before data collection could start).

PN ranging uses a different approach. The ranging sequence is built up from smaller PN sequences, using logical combinations (such as exclusive-OR’ing). The resulting ranging sequence could be on the order of a million bits (or chips) in length. On the receiving side, correlations are done for each of the smaller sequences, not for the entire sequence. Using the smaller sequences is a major savings; for example, a potential code discussed in [9] consists of sequences of length 2, 7, 11, 15, 19, and 23, giving a total ranging sequence of 1,009,470 chips; the total number of correlations needed for doing only the subsequences is 77, instead of the 1,009,470 that would be required if the full sequence were done. The advantage of PN ranging is that the code sequence repeats quickly; for the code mentioned above, the cycle time would be on the order of 0.5 seconds. The acquisition of the downlink ranging signal can start at anytime, since the cycle time of the code is less than 1 second. Also, since multiple cycles of the code are accumulated, independent of the transmission, the integration time can be changed without affecting the uplink signal (e.g., if it is determined that the received signal is weaker than originally predicted, the integration time can be increased, which does not affect the uplinking of the range modulation; for sequential ranging, the uplink signal would have to be changed). The disadvantage of PN ranging is that the downlink ranging power is distributed between the various subsequences; depending on how the code was constructed, the needed integration time can be quite large. This means that care must be taken in selecting the subsequences and the combination logic; in [7] a set codes are proposed that have the necessary properties.

An additional advantage of PN ranging is that the short cycle time allows for a relatively straightforward implementation on a spacecraft of regenerative ranging [9]. Instead of the spacecraft just filtering the ranging signal and then remodulating it onto the downlink carrier, the spacecraft actually detects the signal and then modulates the detected signal onto the downlink. With filtering, the remodulated signal includes
about 1.5 MHz of noise, which, of course, does not contribute to the ranging signal. With regeneration, the noise on the downlink is significantly reduced, which may increase the received ranging signal-to-noise ratio (SNR) by up to 30 dB. Regeneration with sequential ranging is operationally complicated, since the spacecraft would need to know when the cycle started; with PN, the short cycle time removes the need for knowing when the code started.

The trade off between the two types of ranging modulation depends on what is important to the user. Range ambiguity, range sigma, total integration time, and probability of acquisition are all parameters that need to factor into the comparison. In [7] it is shown that there are combinations of PN subsequences that generate ranging codes that perform as well as, if not better than, the equivalent sequential tone configuration. In other words, given three of the above parameters, a PN code can be found that has a better performance for the fourth parameter. This is in addition to removing the operational constraint of needing to coordinate the start of the ranging correlation with the start time of the uplink ranging code, making it a win-win situation.

Implementation of the NSP ranging is described in [10]. The key is the paradigm switch that was made — instead of correlating the signal and then accumulating the result, the signal is accumulated and then correlated. This is possible due to the current DSP technology. Using the same DSP family as is used in the turbo decoder implementation, 16 MHz samples are read into the DSP. The sampling clock is an appropriately scaled version of the received carrier frequency; the scaling is such that the Doppler shift of the ranging modulation is removed in the sampling process. The DSP accumulates the samples into appropriate bins for the necessary time. Then, the correlations are done, at a rate on the order of the integration time of the code. Since the binning and correlating are all done in software, implementing a new ranging modulation type just requires adding the software to define the new ranging code and adding the logic to configure the system for the new code. This could not be done in the old paradigm; since the correlation was done in hardware, a new ranging code type would require new hardware.

Currently, the plan is to implement PN ranging in 2005. New Horizons, the NASA mission to Pluto, is including the hardware to perform regenerative ranging.

5.0 LOW DENSITY PARITY CHECK CODES

Low Density Parity Check (LDPC) codes represent the second generation of "modern" error correcting codes, after turbo codes. In common with turbo codes (and in contrast to earlier codes), decoding uses an iterative belief-propagation algorithm that is sub-optimal, but in practice performs within a fraction of a dB of the theoretical limits. In contrast, a well chosen LDPC code requires about 1/3 as many computations to decode as a comparable turbo code, and those computations are extremely regular and
highly parallelizable. These attributes make LDPC decoders well suited to Field Programmable Gate Array (FPGA) implementation, allowing decoding speeds of 10 Mbps and greater.

LDPC codes were first discovered by Gallager in 1962 [11], but attracted little attention because their decoding was too computationally complex at that time. Shortly after the advent of turbo codes, Gallager's LDPC codes were rediscovered, and they have attracted a great deal of attention by researchers in the last few years. An LDPC code is a block code, defined by a sparse parity check matrix. This matrix can also be represented by a bipartite graph consisting of nodes representing code symbols, nodes representing check equations, and edges showing the constraints imposed on the code symbols by the check equations. Decoding is performed by initializing each code symbol with a likelihood that it is a binary '1', based on the received channel information. These likelihoods are then updated iteratively by using the check equations. This is done by "message-passing" on the graph: code symbol likelihoods are sent to the check nodes, updated, returned to the code symbol nodes, and combined with updated likelihoods from other check nodes. This processing is repeated until all check equations are satisfied, or until some fixed maximum number of iterations is reached. The computations performed at each of the graph nodes in a given iteration are independent of each other, so they can all be performed simultaneously. Moreover, each computation is simple enough that it can be performed by a small circuit. Together, these characteristics make LDPC codes well matched to high-speed decoding using FPGAs.

The design of good LDPC codes is currently an extremely active research area. The primary design challenge is to understand the trade-off between performance, measured in $E_b/N_0$ required to achieve a particular Bit Error Rate, and complexity, measured in decoder speed or some approximation thereof. Just as with turbo codes, many LDPC codes show error floors, where the bit error rate curve shows a sharp decrease in steepness when plotted against $E_b/N_0$. Complexity is directly affected by the average number of iterations required and the density of the code's parity check matrix, and indirectly by the amount of structure incorporated into the parity check matrix. Complexity can also be reduced, at a performance penalty, by approximating the transcendental computations required. Many improvements have been made on each of these issues in the last few years. While all of these remain open research topics, enough has been learned that several research groups have built hardware LDPC decoders, and standardization of LDPC codes is underway. A draft standard has been written for Digital Video Broadcast (DVB) specifying encoded block lengths of 16200 and 64800 bits, with code rates ranging from 1/2 to 9/10. Standardization discussions are also underway at CCSDS. There are no commercial applications of LDPC codes yet, but they can be expected soon.

For the DSN, an LDPC decoder would be installed as a parallel path to the turbo decoder, and would be integrated into the TLP exactly as the turbo decoder has been (symbols plus time tag information as the input, decoded frames as the output). The decoder would be a VME card consisting of FPGAs to perform the LDPC decoding, and a microprocessor to handle control and communications issues. Frame
synchronization would be done in the symbol domain, as it is for turbo codes. There is no funded plan yet for implementing the LDPC decoder, but it is expected that as the CCSDS converges to a standard, high rate missions will require its capabilities (for example, proposed high rate missions such as the Mars Telecom Orbiter or the Jupiter Icy Moons Orbiter may have the need for LDPC performance).

6.0 CONCLUSION

The new TT&C architecture of the DSN allows for the addition of new capabilities to provide greater performance for missions. Specific examples that have been presented are Turbo decoding, which has already been implemented, PN ranging, which has its implementation about to begin, and Low Density Parity Check decoding, which is still under consideration. These three examples show that the new architecture provides a framework for adding new features as technology and development create them.

7.0 REFERENCES


8.0 ACKNOWLEDGEMENTS

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9.0 BIOGRAPHY

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