The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

NEXT GENERATION UPLINK

INFORMATIONAL REPORT

CCSDS 230.2-G-1

GREEN BOOK

July 2014

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This CCSDS Informational Report is provided as a result of the Interagency Operations Advisory Group (IOAG) resolution for CCSDS to develop a future set (next generation) of telecommand recommendations for space missions. Future missions may require the following:

a) a higher rate uplink (sustained data rates of megabits per second and occasional data rates of tens of megabits per second) than the current limit of 2 Mb/s under the current set of CCSDS Recommended Standards;

b) higher performance (data rate and/or distance) from the available antennas and transmitters;

c) improved ranging performance and time correlation utilizing regenerative ranging.

These missions are likely to include multinational participation and, as such, will require interoperability and cross-support of telecommunications services.

The links need to be power efficient because of limited EIRP, to be highly reliable, to accommodate emergency services operating with very limited access windows, and to be implementable with limited onboard complexity.

Applications to consider include: deep space emergency uplink, nominal commanding, file uploads, and potentially human support applications.

Existing CCSDS Recommended Standards for uplink signaling do not provide an adequate solution for the entirety of future needs. The limitations in uplink data rate of the current CCSDS telecommand Recommended Standards accommodate the following rates:

a) low rate telecommand: PSK modulation on rates up to and including 4 kb/s using an 8 or 16 kHz subcarrier requiring a received power level of 9 dB;

b) medium rate telecommand: PCM/PM/Bi-Phase modulation direct onto the carrier for rates between 8 kb/s and 256 kb/s;

c) high rate telecommand: BPSK modulation direct onto the carrier for rates up to 1 Mb/s.

It is important to note that these higher data rates will be required for normal operations but it is reasonable to expect that these links must support emergency operations.

1.2 APPLICABILITY

This document is a CCSDS Informational Report and contains descriptive materials and supporting rationale for missions that require telecommand capabilities beyond those supported by CCSDS member agencies today.

1.3 RATIONALE

The rationale for the development of a Next Generation Uplink by CCSDS member agencies includes the following:

a) A long lead time is required to develop and interoperability test new recommendations. At least four years are required to budget, design, build, and test a new telecommand capability and hardware to perform them.

b) Onboard applications are tending to require larger volume uplinks than in the past. Today’s spacecraft are storehouses for software which include software for Field Programmable Gate Arrays (FPGAs) or programmable Application Specific Integrated Circuits (ASICs) which are rapidly replacing unique hardware systems. State-of-the-art onboard telecommunication systems are deploying ‘software radios’ implemented in FPGAs or ASICs that can be easily reprogrammed in flight and support quantized bit outputs (required for higher performance codes). Moreover, changes to flight software applications occasionally require the uplink to deliver very large volumes of reprogramming data.

c) The trend towards increased use of selective repeat protocols on the uplink puts greater demands on uplink throughput. Higher rate downlink missions that use selective-repeat-Automatic Repeat reQuest (ARQ) may require acknowledgements in addition to the acknowledgements for reliable uplink file data transfers. Typically for robotic missions, the telemetry data rate is much higher than the command data rate. If CFDP is used on the downlink, there is a concern that this protocol's return traffic back to the spacecraft (i.e., CFDP Finish PDU, a type of overall positive acknowledgement) and Negative AcKnowledgements (NAKs) will consume too much uplink bandwidth. Even in the case of no NAKs being sent, a Finish PDU is required to be sent up from the ground for each complete file received. The following example illustrates the problem: With a downlink rate of 30 Mb/s and 6 Mb files, CFDP has to transfer 5 Finish PDUs to the spacecraft per second. Each Finish PDU contains about 20 bytes (160 bits). Thus the required uplink traffic for positive acknowledgements alone is approximately 800 b/s which is 40% of the current maximum uplink traffic available at 2,000 b/s. Moreover, this bandwidth must remain dedicated to the CFDP return channel for the entire pass.

d) Deep space missions typically operate with large margins (at least 3 dB) on the uplink in order to ensure a robust communications link to the spacecraft. Typically these missions operate over links that provide a Bit Error Rate (BER) of 10^{-5} or better. Consequently missions are typically very conservative on the uplink margin. For example the recently completed NASA Deep Impact mission operated with an uplink margin of 17 dB at encounter at maximum range from 34-m Deep Space Network (DSN) stations (mean minus 3-sigma for 2 kb/s uplink data rate with 3 dB of additional ranging modulation). This additional margin translates into a factor of 50 greater uplink throughput, if that available coding gain can be harvested. By reducing that margin by 3 dB or even 6 dB, the uplink data rate can be increased by a factor of 2 and perhaps as high as 4. The idea is to reduce the margin to the point where occasional errors (10^{-3} BER) can occur. These errors result in a limited number of file segments to be retransmitted using a selective repeat protocol, i.e., CFDP. As long as there is sufficient round-trip light time to complete the retransmission of file segments in error, CFDP would be used. However, when the round-trip time is insufficient to request and receive missing file elements, then the sender would preemptively retransmit, i.e., send duplicate portions of the file. Since the probability of missing the same file segment equals the square of the probabilities of losing a single segment for independent file losses, this type of loss event is small and is very unlikely to occur.

e) Spacecraft mass constraints can be ameliorated by reducing the size/mass of spacecraft receiving antennas supporting emergency conditions. Thus a medium gain antenna required today to support ‘Safe Mode Operations’ could possibly be accomplished using a smaller diameter antenna.

1.4 DOCUMENT STRUCTURE

This document is divided into six numbered sections:

a) section 1 (this section) contains administrative information, definitions, and references;

b) section 2 presents an overview of the current state of telecommand and the motivation for the next generation uplink;

c) section 3 presents reports on how advanced channel coding techniques affect the uplink;

d) section 4 addresses the application profiles and their associated figures of merit that the next generation uplink protocol will satisfy;

e) section 5 contains the uplink channel coding trade studies conducted;

f) section 6 addresses randomization under different coding assumptions.

1.5 CONVENTIONS AND DEFINITIONS

1.5.1 GENERAL

Within the context of this document the following definitions apply.

1.5.2 DEFINITIONS FROM THE OPEN SYSTEMS INTERCONNECTION BASIC REFERENCE MODEL

This document is defined using the style established by the Open Systems Interconnection (OSI) Basic Reference Model. This model provides a common framework for the development of standards in the field of systems interconnection.

The following terms, used in this Report, are adapted from definitions given in reference [1].

layer: A subdivision of the architecture, constituted by subsystems of the same rank.

protocol data unit, PDU: A unit of data specified in a protocol and consisting of protocol control information and possibly user data.

service: A capability of a layer (service provider), together with the layers beneath it, which is provided to the service-users.

service data unit, SDU: An amount of information whose identity is preserved when transferred between peer entities in a given layer and which is not interpreted by the supporting entities in that layer.

1.6 REFERENCES

The following documents are referenced in this Report. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Report are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS documents.

[1] *Information Technology—Open Systems Interconnection—Basic Reference Model: The Basic Model*. 2nd ed. International Standard, ISO/IEC 7498-1:1994. Geneva: ISO, 1994.

[2] *TC Synchronization and Channel Coding*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 231.0-B-2. Washington, D.C.: CCSDS, September 2010.

[3] *TC Space Data Link Protocol*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 232.0-B-2. Washington, D.C.: CCSDS, September 2010.

[4] *Communications Operation Procedure-1*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 232.1-B-2. Washington, D.C.: CCSDS, September 2010.

[5] *Space Data Link Security Protocol*. Issue 3. Draft Recommendation for Space Data System Standards (Red Book), CCSDS 355.0-R-3. Washington, D.C.: CCSDS, October 2013.

[6] *AOS Space Data Link Protocol*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.0-B-2. Washington, D.C.: CCSDS, July 2006.

[7] *TM Space Data Link Protocol*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 132.0-B-1. Washington, D.C.: CCSDS, September 2003.

[8] T. De Cola, et al. 'Reliability Options for Data Communications in the Future Deep-Space Missions.' *Proceedings of the IEEE* 99, no. 11 (Nov. 2011): 2056–2074.

[9] L. Costantini, et al. 'Non-Binary Protograph Low-Density Parity-Check Codes for Space Communications.' *International Journal of Satellite Communications and Networking* 30, no. 2 (March/April 2012): 43–51.

[10] G. Liva, et al. 'Turbo Codes Based on Time-Variant Memory-1 Convolutional Codes over F_q.' In *Proceedings of 2011 IEEE International Conference on Communications (ICC) (5–9 June 2011, Kyoto)*. 1–6. Piscataway, NJ: IEEE, 2011.

[11] G. Liva, et al. 'Codes on High-Order Fields for the CCSDS Next Generation Uplink.' In *Proceedings of 2012 6th Advanced Satellite Multimedia Systems Conference (ASMS) and 12th Signal Processing for Space Communications Workshop (SPSC) (5–7 Sept. 2012, Baiona)*. 44–48. Piscataway, NJ: IEEE, 2012.

2 CURRENT VS NEXT GENERATION UPLINK PARADIGMS

2.1 OVERVIEW

In the 1970s, spaceborne digital technology was emerging, digital flight hardware was heavy, and required a lot of power, thus limiting the complexity that could be implemented in the spaceborne transceiver and command decoder. Thus drivers behind the creation of Telecommand protocols stem from that era, namely:

a) simple uplink coding was employed primarily to detect transmission errors for near-Earth missions and to correct-single bit errors within each codeword primarily for deep space missions;

NOTE – Even current flight receivers only output hard symbols limiting coding performance.

b) commanding rates were very limited; and

c) onboard flight controllers were simple with little or no memory, thus requiring few commands to operate them.

Traditionally, uplink communication has been used primarily for telecommand control, where short command sequences were transmitted to an unmanned spacecraft a few times per day to a few times per month. Thus the design of the telecommand solution emphasizes high reliability, utilizing often very short commands, and implementation simplicity. Current and future spacecraft use uplink communication for a much wider variety of uses, increasingly treating the uplink as just another general-purpose communications link within a larger network. While telecommand continues to be an essential application, both in normal and emergency situations, there is increasing demand for transmitting larger volumes of data to a spacecraft that may even be at a greater distance from Earth. These other general-purpose uses bring with them attendant concerns of reliability, security, low-latency, and interoperability.

The CCSDS TC Protocols (references [2]–[3]) evolved from the early NASA telecommand protocols. The CCSDS added the capability to extend the size of command messages and added both a Cyclic Redundancy Check (CRC) and a simple ARQ protocol to improve the reliability for larger message sets. Current and future spacecraft require the use of uplink communication for support of a growing wider variety of uses. While telecommand continues to be an essential application, both in normal and emergency situations, there is increasing demand for transmitting larger volumes of data to a spacecraft to support ever increasing reprogrammable implementations. There are various sources of these new demands on uplinks and with them come concerns of reliability, security, low-latency, and interoperability.

Inclusion of manned missions integrated into the services that were developed for robotic missions will open the door for the assessment of a improved uplink protocol that can support both the manned missions and the robotic missions needing direct-from-Earth communications.

A growing practice is the use of selective repeat protocols on the uplink such as with CFDP. Higher rate downlink missions that use selective-repeat-ARQ require higher uplink data rates to provide status and acknowledgements for the transfers. There are ever-growing requirements for reliably delivering large operational data files. For example,

a) modern flight equipment can be reprogrammed, both with software for microprocessors and ‘logicware’ for FPGAs or ASICs;

b) there is a growing need for added uplink security adding considerable size to the minimum command size, and manned missions require interactive voice, video, and Internet access.

With the advent of modern coding techniques, very considerable improvement is possible over the existing Bose-Chaudhuri-Hocquenghem (BCH) codes specified in the *TC Synchronization and Channel Coding* Blue Book (reference [2]). Identifying more powerful codes is a central element of the upgraded recommendation. The performances achievable from these codes, however, require the upgrading of current transponders to operate at lower symbol-signal-to-noise levels and to output soft symbols. Fortunately, transponder technology is currently available to meet those needs and thus enable the improvements in uplink communications.

Besides the BCH codes, telecommand provides reliability mechanisms via a CRC and its own ARQ mechanism via the Communications Operation Procedure 1 (COP-1) protocol (reference [3]). COP-1 is deliberately based on a very simple go-back-*n* repeat mechanism, but for that reason it is unsuitable for missions with very long propagation delays. Long round-trip delays result in equally long interruptions in the command sequence, so that in practice, COP-1 can only be used inefficiently in deep space missions. The proposed telecommand protocol upgrade will provide improved performance that will better support a more robust telecommand ARQ, which could be implemented at higher protocol layers e.g., Licklider Transmission Protocol (hop-by-hop), SCPS-TP (end-to-end), or Bundle-Protocol, suitable for long-delay scenarios. NGU will provide for larger frames that would require a smaller number of LTP segments or even carry complete bundles.

A CCSDS working group is separately addressing communication security concerns, such as authentication and confidentiality, as these apply to all space data links. The new telecommand recommendation will include Data Link Layer security extensions as indicated by the Space Data Link Security Protocol (reference [5]).

The existing telecommand standards (reference [2]–[4]) were driven by the special characteristics of practical forward data links combined with the particular concerns of spacecraft commanding. The results are protocols and standards of uplink and downlink being substantially distinct: different in the use of specific codes, different in services, different in the use of fixed vs. variable transfer frames, and different in the use of variable-length vs. fixed-length transfer frames. These differences complicate the task of achieving a networked architecture. They also complicate effective re-use of solutions between uplink and downlink, or other space data links for that matter. The proposed upgrade will provide for better alignment with emerging network standards, e.g., DTN which also uses LTP.

Again, telecommand continues to be an essential application, both in normal and emergency situations. The intent of these new recommendations is to strengthen telecommand in several key areas while retaining its essential structure and purpose. To the extent possible, the original layering principles will be observed and preserved.

2.2 CURRENT UPLINK ARCHITECTURE

The current uplink architecture standards are designated as Telecommand (TC). Telecommand must deal with the same challenges inherent in all space link communications, while focusing on the special issues of uplink: relatively low-rate links, sporadic commanding, and commanding in emergencies. One issue of particular interest is the inherent sensitivity of spacecraft commanding, since an undetected command error can spell disaster for the spacecraft. Reliability is paramount for telecommand with the principal metric being a low undetected error rate.

There are many common issues with space communications links that all the space link protocols must address, usually with broadly similar solutions. The problems of noisy, long-delay links indicate the use of forward error correction techniques. The need to detect the beginning of a frame leads to the use of a reserved bit pattern as a synchronization marker. The problem of detecting bit transitions in the radio signal is aided by randomizing techniques. And in general, each of these potential solutions must be weighed against the risk of imposing overly burdensome computational, storage, or power demands on the spacecraft. Given the wide range of choices within these categories, each with its own set of trade-off issues, it is not surprising that specific integrated solutions can vary greatly in the details. For example, the details of the Telecommand architecture vary substantially from the details of the Telemetry architecture. This section explores those distinctive features of the uplink architecture seen as relevant to the Next Generation Uplink recommendations.

The current telecommand standards recommend a modified BCH code. This code can be employed either in error-correcting mode, the Single-Error-Correction (SEC) mode, and/or in pure error-detection mode, the Triple-Error-Detection (TED) mode. Another important uplink metric is a low probability of rejection, which is easier to meet with an error-correcting mode. While the BCH code is not an efficient code by today's standards, it has some important virtues from the standpoint of uplink. The BCH makes use of very short codewords (64 bits), making it well-suited for representing a variable-length transfer frame (codeblock) with a variable series of codewords. Further, the BCH offers one of the simpler onboard implementations. The preference for implementation simplicity remains a key metric, though clearly more so for legacy spacecraft.

As is typical for trade-offs, while the use of error-correcting mode helps lower the rejection rate, it may come at the cost of raising the undetected error rate. For situations like this, the telecommand standard provides an option of adding a CRC in order further to reduce the undetected error rate.

When error-correction fails (or is not used), the current telecommand standard utilizes COP-1 as the ARQ process to deliver reliable and complete commands as an optional procedure. COP-1 essentially returns to the set of ordered commands at the point of the error and restarts the transmission. This very simple technique is described as 'go-back-*n*' as compared to the more targeted technique described as 'selective repeat'. Despite its relative simplicity, the COP-1 does require many cooperating elements: a Frame Operating Procedure (FOP) to administer source frame transmission, a Frame Acceptance and Reporting Mechanism (FARM) for detecting and reporting missing or out-of-order frames, and a Communications Link Control Word (CLCW) for reporting error frames conveyed back to the source by means of TM (reference [7]) or AOS (reference [6]). Again, the relative simplicity of the algorithm is a virtue that comes at the cost of efficiency. The COP-1 technique can result in a lengthy halt of the command sequence in cases where the round-trip time is long. These long round-trip times are characteristic of deep space missions, and the go-back-*n* retransmission mechanism of COP-1 is not effective for them; as a result, deep space missions use alternative or complementary techniques to ensure reliable command delivery.

The foregoing describes some of the more notable elements of the current uplink architecture, particularly those that are subject to revision under the Next Generation Uplink. The full uplink architecture is a protocol stack extending through the data link protocol, channel coding, and physical layer. As is customary in CCSDS protocol standards, the telecommand protocols are organized as a layered stack including physical, channel coding, and data link protocol. This layered model is largely modeled on the well-known seven-layer communications model of the OSI Basic Model, though there are some specific differences, such as the special issues of radio communications with coding and synchronization.

This layered architecture can also be seen in the structure of the principal TC protocol books. Upper layers are specified in the *TC Space Data Link Protocol* providing the functions of segmenting, blocking, and transmission control. These are considered two layers: the segmentation layer and the transfer layer. A lower layer is specified in the *TC Synchronization and Channel Coding* Blue Book, providing the functions of error control, synchronization, pseudo-randomization, and repeated transmissions. This lower layer is considered the coding layer.

The layered architecture provides a certain order to the recommendations and provides the designer with some useful options for safely making localized changes within a layer. In practice though, the telecommand stack largely stands by itself, distinct and separate from other comparable space data link protocol stacks.

2.3 RECENT ADVANCES

There have been numerous technology advances in recent decades that are substantially changing the character and context for newer missions and changing the mix of potential solutions. This subsection focuses principally on technology advances that can offer new choices for the uplink architecture.

Modern coding techniques offer very large improvements in performance. In particular, the Low Density Parity Check (LDPC) family of codes can approach the theoretical limits of efficiency as established by the Shannon sphere-packing bound. While the LDPC codes were discovered long ago, it has been the development of practical decoding algorithms and hardware advancements that now make LDPC so attractive. These new decoding algorithms, described as Belief Propagation (BP), provide near-optimum performance with manageable complexity. In comparison to the BCH codes presently used by TC, an LDPC code can achieve the same error floor with a reduction in power requirements of between 2.5 and 8.5 dB. Additional 1.5 dB can be achieved by non-binary LDPC codes on large-order finite fields (reference [8]).

Past decades have also seen further developments in space link and transport protocols, such as AOS, PROX-1, CFDP, DTN, and LTP. Among other things, these new protocols have come with various new ARQ techniques. This is a recurring theme, where ARQ serves as the reliability mechanism of last resort when the various forward error correction schemes fail to deliver a data unit successfully. As previously explained, the COP-1 ARQ mechanism is very inefficient under conditions of long round-trip delays or repeated commands, so some form of selective-repeat-ARQ is more attractive. Generally, a selective-repeat-ARQ targets the missing data unit(s) and does not cause any delay in concurrent transmissions. Among those supporting selective-repeat, the ARQ of LTP appears to be the most promising. LTP offers an optional selective-repeat-ARQ that can be adapted to any of the underlying space data link protocols, while remaining low enough in the stack to offer maximum flexibility for use at higher layers. The LTP ARQ is neutral with respect to the ultimate data format, in contrast to, for example, the CFDP ARQ, which is specialized to entire files.

2.4 KEY TRADE-OFFS

There are four trade-offs that need to be considered before a Next Generation Uplink protocol can replace the existing TC Recommended Standards (references [2]–[4]).

Selection of the Data Link Layer Protocol

The options are 1) TC Space Data Link Protocol or 2) AOS Space Data Link Protocol (see table 2-1).

The requirement for short emergency commands when data rates are limited favors the TC protocol. As long as space agencies cannot relax the requirement and require the use of short commands, i.e., between 56 to 256 bits for emergency commanding, then TC seems to be the prudent choice. The driver behind the use of short commands in the emergency case is the latency involved in receiving these commands when the view period is short, constrained by a tumbling spacecraft that is intermittingly able to receive the uplink. Latency mainly depends on symbol acquisition time and codeblock/frame size. A codeblock could be composed of one codeword at low rates and a series of concatenated codewords allowing the frame size to be larger for higher rates with small implementation cost. In that way, one could concatenate a series of smaller codewords into a larger codeblock containing a larger frame.

Table 2-1: Data Link Layer Protocol Tradeoff

	TC	**AOS**
Mission Usage	Unmanned Missions	Manned Missions
Fixed vs Variable length Frames	Variable Length Frames	Fixed Length Frames
Payload	Packet, Segment, Byte Stream	Packet, Byte Stream, Bit Stream
Short Commands (i.e., required in emergency mode)	Advantage—low latency & small codeword size	N/A
Long Commands (e.g., nominal commanding, file transfer, etc.)	N/A	Advantage—use of larger size codeword to obtain better performance
SLE/CSTS Service Impact	No Impact	Changes Required

FEC Code Trade Space

One or multiple Forward Error Correction (FEC) codes with associated code rate (n,k), where n equals the number of information bits and k equals the number of message bits, and codeword size need to be considered. These figures have been computed using a CodeWord Error Rate (CWER) of 10^{-3} and an Undetected CWER (UCWER) of 10^{-6}. The values generated below used decoding algorithms with a maximum number of decoder iterations set to 100. It should be noted that the short (64,128,256) LDPC codes converged in much less than 100 interactions. The options are given in table 2-2.

Clearly the largest coding gain is achieved using the largest LDPC codeword size of 16384. However, that comes at a price of increased latency of reception of the commands and implementation of the decoder. An interesting comparison can be seen between the LDPC (512, 256) and the BCH(56,64) codes. The current minimum emergency command size that is often quoted is 56 bits based upon the information size of a BCH codeword. The use of the LDPC (512, 256) code would accommodate this 64-bit command and would allow for the inclusion of 192 bits for link security as defined in reference [5]. The use of non-binary LDPC codes over a finite field of order 256 may bring an additional 1 dB gain over the binary LDPC codes for block lengths of 128, 256 and 512 bits (reference [10]). The (512,256) can, with the same configuration and operating condition, accommodate four times the data rate over the current BCH code and thus deliver a 256-bit command within the same time period required currently to deliver a 56 bit command. The minimum command period would be 512 symbols and around 64 symbols for frame sync (total 288 bit times) plus the time to acquire symbol synchronization. It should be noted that, from a systems perspective, once uplink security becomes a mandatory need, these extra bits provided by the larger codeword will be useful in implementing the security algorithms in the emerging CCSDS Space Data Link Security Standard (reference [5]).

Table 2-2: FEC Selection Tradeoff

Code rate, (*n*,*i*)	**Code E_b/N_o operating point Frame TC/AOS**	**Performance Impact**
BCH (56,64)	~9.6 dB (TC—SEC/DED)	Current TC baseline
R-S(10200,8920)+ CC(7,1/2)	~2.3 dB	Current AOS baseline (for downlink)
LDPC ½, (128,64)	~4.3 dB (TC)	~5.3 dB better than BCH
LDPC ½, (256,128)	~3.6 dB (TC)	~6 dB better than BCH
LDPC ½, (512,256)	~3 dB (TC)	~6.6 dB better than BCH; send (64,56) code 4× faster but same window as current TC
Non-Binary LDPC ½, (128,64) (reference [9])	~3.3 dB (TC)	~6.3 dB better than BCH
Non-Binary LDPC ½, (256,128) (reference [9])	~2.6 dB (TC)	~7 dB better than BCH
Non-Binary LDPC ½, (512,256) (reference [9])	~2 dB (TC)	~7.6 dB better than BCH
LDPC ½, (8192,4096)	~1.2 dB (AOS)	~1.1 dB better than concatenated R-S/CC
LDPC ½, (16384,8192)	~0.9 dB (AOS)	~1.4 dB better than concatenated R-S/CC

The use of the LDPC (2048,1024) code would provide a gain of 1.4 dB over the CC-RS baseline, but would require about three times the radiation time period. An even larger LDPC code can be used with this same approach, but it seems that it would be better suited to AOS, where the frame size is fixed, if the current emergency mode requirement for reception of a short emergency command within a short receiving time window is no longer required.

So there remain some important tradeoff questions to be considered when choosing such codes for standardization:

a) Can a single FEC command code satisfy the totality of a mission's needs (latency, EIRP)?

b) Can a single mission utilize multiple FEC codes (at least two: perhaps one for emergency mode and the other for nominal operations) without adding excessive implementation complexity?

c) Can a single FEC command code be used to provide short commands for emergency conditions while using a defined or determined number of codewords from the same code, in series, to provide the means to deliver a much larger command frame for nominal operational conditions?

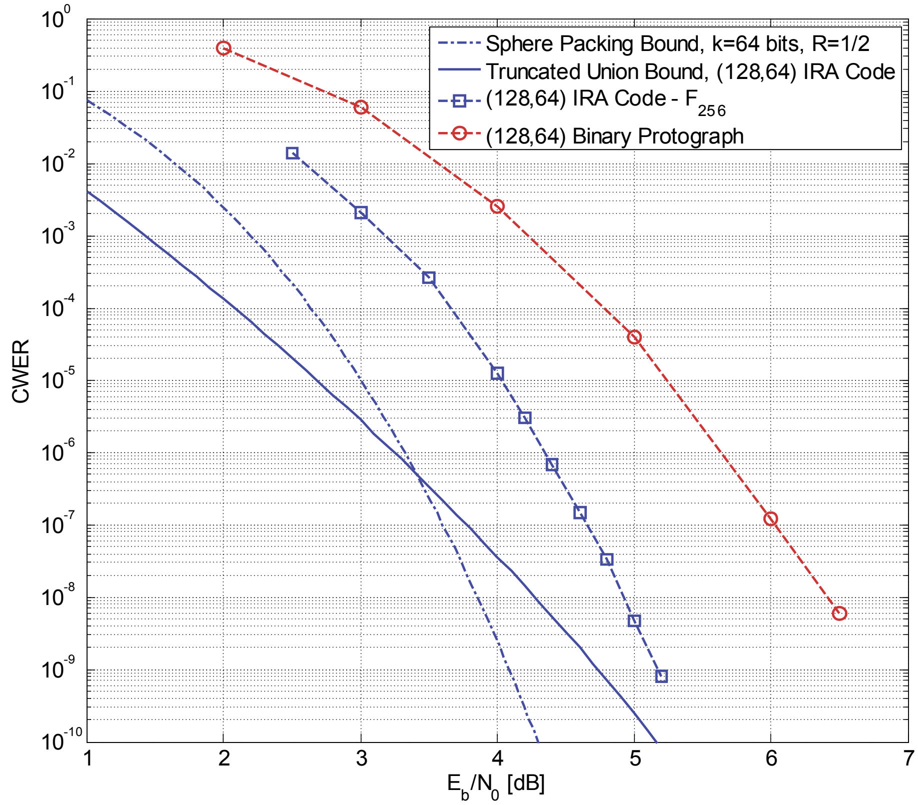

Figure 2-1: Performance of a (128,64) Non-Binary LDPC Code (IRA-Like) over a Field of Order 256 with Respect to the Binary (128,64) Protograph-Based LDPC Code[1]

Selection of the Synchronization Word

The options to be considered for selection of the synchronization word are: 16 bit, EB90 hexadecimal (BCH) vs. 64 symbol, 034776C7272895B0 hexadecimal (LDPC).

The selection of the synchronization word size depends upon the selected code, the operating symbol Signal-to-Noise Ratio (SNR), and whether idle is allowed between frames. A very high probability of obtaining synchronization in one synchronization word is needed for command; i.e., the probability of missed frame detection must be very low (10^{-3} CWER).

Selection of Command Link Transmission Unit (CLTU) Termination

The options to be considered for selection of CLTU Termination are:

a) An erred codeword terminates the codeblock (current baseline).

b) Use of a signaling byte in each codeword to identify the last codeword in the CLTU.

[1] (See reference [11].)

The signaling byte could simply be a defined codeword or it could be used as a count-down counter until the defined codeword is encountered, which indicates this codeword is the last one in the CLTU. This method requires that the total length of the CLTU be known when starting the encoding process. From an efficiency point of view, there is 100% overhead for those commands that only require one codeword, if approach a) is used. Approach a) becomes more efficient for longer commands. This approach is significantly more efficient for short commands using short LDPC codewords, as illustrated below for the LDPC ½, (256, 512) example in table 2-3.

c) Use of the TC frame length field.

The TC frame length field provides the unambiguous size of the telecommand frame, when the number of TC frames per CLTU is limited to one. This new limitation would require a change to the current TC standard, namely limiting the number of TC frames within one CLTU to one frame. It should be noted that there are no known CCSDS missions to date that utilized more than one TC frame per CLTU.

Table 2-3: Codeword Termination Method Tradeoff (Illustrated for LDPCC Only)

Command Size	Signaling Byte per Codeword Overhead (method 2)	Erred Codeword Overhead (method 1)
256 bits	8/248 ~ 3.2%	256/256 = 100%
1024 bits	32/994 ~ 3.2%	256/1024 = 25%
8196 bits	256/7940 ~ 3.2%	256/8196 ~ 3%

Approach b) is significantly more efficient for long commands using long LDPC codewords as illustrated below for the LDPC ½, (16384, 8192) example in table 2-3. It should be noted, however, that the use of fixed codewords and variable frames could require substantial overhead because the number of codewords required to contain the frame could contain a significant number of extra bits contained in the frame.

3 UPLINK CODING FOR NEW TC STANDARD

3.1 INTRODUCTION

With the advent of modern coding techniques, considerable improvement is possible over the existing BCH codes specified in the *TC Synchronization and Channel Coding* Blue Book (reference [2]). Moreover, spacecraft and their communications protocols continue to become more complex, and so there is a corresponding demand for more sophisticated uplink coding capabilities.

Traditionally, uplink communication has been used for navigation and command. The telecommand volume has been small and, where short command sequences were transmitted to an unmanned spacecraft, transmission has been limited to a few times per day to a few times per month. Future spacecraft will require the uplink communication to deliver a much higher command volume. While navigation continues to be an essential application, both in normal and emergency situations, there is increasing demand for transmitting larger volumes of data to spacecraft because flight equipment can be reprogrammed, both with software for more competent processors and 'logicware' typically implemented in either ASICs or FPGAs. Manned missions are dictating very high rate uplinks to support uplink video and Internet access.

The space telecommunications environment is ever evolving. In some cases there may be many spacecraft in a small solid angle as observed from Earth, such as in the Mars vicinity or at a lunar outpost, and there is interest in serving Multiple Spacecraft Per Antenna (MSPA). Despite these changes, some facts hold constant: distances in deep space are immense, and received signal power is correspondingly miniscule. Power efficiency remains a dominant priority. A spacecraft emergency requires the telecommunications system to deliver the Earth-based controller's commands, and there must also be a method to deliver short commands at an extremely low data rate when necessary.

The Next Generation Uplink (NGU) initiative identifies a greater variety of uplink needs. The command needs are categorized into five modes as summarized in table 3-1. These different command application profiles place different demands on the telecommunications link, and hence the error correcting codes chosen for each application may also be different. The uplink is used in combination with the downlink to support the navigation function. The inclusion of a complex correlator with the newer transponders to enable regenerative ranging and time correlation capabilities improving the navigation and the clock-correlation application performances.

In this document, one systematic method of selecting FEC codes for each of these applications is pursued. Subsection 3.2 lists several Figures Of Merit (FOMs) that can be determined reasonably quantitatively for a coding system. Section 4 expands upon each of the modes listed in table 3-1 and contains an application profile for Modes A through E. Section 5 discusses the trade studies associated with these modes. In each case, several candidate codes are listed, their FOMs are tabulated, and based on the relative significance of these FOMs, suggested codes are selected.

Table 3-1: NGU Baseline Application Profiles

	Application Profile Name	*Transmission Rate Range (kb/s)*	*Message Size (kb)*	*Characteristics*
A	Proposed Deep Space Emergency Commanding	.032	.250	Best Effort, Max Reliability (both Link & Hardware) Short window for access Use of advanced codes
B	Current Nominal Command Rate CCSDS Uplink	.1–4	1–4	Sequential Delivery immediate execution
C	Current Sequence and Software File Uploads	.1–4	4	Sequential and/or Selective Repeat delivery with delayed execution
D	Manned Missions Nominal Uplink	256–20,000	8–16	Selective Repeat for IP delivery of eng., voice, video

3.2 FIGURES OF MERIT

3.2.1 GENERAL

The characterization of an error correcting code for uplink channels can be made based on investigating candidate codes relative to a number of FOMs. For each application scenario, requirements on the FOMs can be established. Some of these requirements are thresholds, and any code that cannot meet the threshold is rejected. For example, if command uplink requires an undetected error rate below 10^{-9}, any code that cannot meet that threshold is rejected. Other requirements are weights, and the final code can be selected by minimizing the weighted sum of these FOMs. For example, file upload depends little on link latency, so a small weight is assigned to this metric, and a code with high latency is little penalized.

The following list of FOMs is not in any particular order, but the more important and more quantitative metrics tend to be listed earlier. Specific priorities will depend on the application.

3.2.2 POWER EFFICIENCY (E_b/N_o REQUIRED TO GET TARGET QUALITY OF SERVICE)

The power efficiency metric is listed first because the purpose of an error correcting code is to reduce the amount of energy needed to achieve a given level of reliability. The reduction is the *coding gain* of the code. The power efficiency of a code is determined by measuring the bit SNR (E_b/N_o) required to achieve *both* the target CWER and undetected CWER (see below). This is an important point because the difference in SNR needed between the two can be 2.5 dB or more. In the case of uplink coding, there are two related reliability targets: the codeword error rate P_w, and the undetected error rate P_u.

3.2.3 QUALITY OF SERVICE (REQUIRED ERROR RATE)

3.2.3.1 Codeword Error Rate (P_w)

P_w is the fraction of codewords that are in error, and $P_w = P_d + P_u$, where P_d is the fraction of codewords that are detected to be in error and P_u is the fraction that are undetected errors. P_d is also called the rate of decoder failure, since the decoder will refuse to decode these codewords. Even a single bit error may produce a codeword error, and if the latter is a detected error, the entire codeword is generally discarded. As such, codeword error rate is a more appropriate measure than, for example, BER. In some uplink scenarios, it is acceptable for P_w, also sometimes referred to as the Word Error Rate (WER), CWER to be somewhat higher than that required for a downlink telemetry signal. One reason for this is that commands are sometimes sent repetitively, and in any case missing a single command is not usually problematic.

3.2.3.2 Undetected Codeword Error Rate (P_u)

P_u is a measure of the fraction of outputs of the decoder that are incorrect codewords *and cannot be flagged as such by the decoder or subsequent processing.* This is a critical difference from P_w. It is acceptable for the spacecraft to discard a command with an error in it and wait for it to be retransmitted, but it is potentially catastrophic for the spacecraft to fail to recognize that a command contains an error and execute it by mistake. Therefore uplink coding must guarantee a very low P_u. One way to achieve this is by using a CCSDS recommended CRC in the Frame Error Control Field.

3.3 THROUGHPUT

One of the fundamental requirements placed on a communications link is the number of bits per second it can deliver. Bits refers to the number of information bits, not the number of code symbols, and so it differs from the bandwidth required by two factors: the code rate and the modulation order.

3.4 SPECTRAL EFFICIENCY / BANDWIDTH

The spectral efficiency/bandwidth metric is critical for high rate communications links that encounter bandwidth limitations. It is generally not of concern for emergency uplink, which uses a relatively low data rate, but is relevant for high rate uplink.

3.5 LATENCY

The latency of a code is the time elapsed from the appearance of a source bit at the channel encoder to the reproduction of that bit at the decoder, not counting the transmission delay. Typically, the duration of a source bit is assumed to be much greater than the clock time of the hardware, so that signal processing may be modeled as instantaneous. Therefore from a coding perspective, the latency is directly associated with the codeword length. The delay due to transmission over the physical channel, a constant for all codes, is irrelevant for this comparison and disregarded.

For stream-based communications systems (e.g., uncoded and convolutionally coded data, *if* no frame or packet structure is used), the latency is the same for all bits, once acquisition has taken place. For block codes or frame-based systems, the first bit of a codeword has higher latency than any other bit of the codeword, and the latency of the code is defined to be the latency of this first bit.

3.6 ACQUISITION TIME

Signaling schemes require time to acquire the first symbols, a metric separate from the steady-state latency seen after acquisition. In the case of convolutional codes, the acquisition is the time necessary to establish node synchronization (if the stream is not framed). For block codes, the acquisition is the time necessary to establish frame synchronization. The time to acquire the carrier signal and symbol time is independent from the choice of code.

3.7 DECODER COMPLEXITY

The complexity of decoding a code is important because a spacecraft typically has limited resources to dedicate to this operation. One measure of complexity is the number of operations needed per decoded bit. Other factors include the amount of memory required, and whether the encoder and decoder are more suitable for hardware or software implementations.

3.8 MATURITY / LEGACY / COTS AVAILABILITY

The Technology Readiness Level (TRL) of candidate schemes is an important metric. The availability of proven implementations and availability from commercial vendors is also important. This includes space-qualified decoders.

3.9 COST: USER BURDEN AND INFRASTRUCTURE BURDEN

There is a financial cost in supporting an error correcting code, both to the spacecraft and to the ground-based infrastructure. Spacecraft costs include the flight-qualified decoder hardware and the time for debug and test, and these costs impact every spacecraft built. The ground-based encoder hardware is typically relatively simple, need not operate in a flight environment, and need only be paid once when the service is added. However, many copies may be required for each ground station, and there are ongoing maintenance and training costs.

3.10 ADAPTABILITY

For missions which expect varying uplink conditions throughout their lifetimes (e.g., cruise-phase and prime-phase), it may be helpful for more than one mode of uplink coding to be available. This may mean standardizing multiple uplink codes. With such multiple codes, it is helpful for them to be related members of a class of codes, so that a spacecraft wishing to implement multiple decoders may use a single overall design that works with multiple codes.

3.11 RECEIVER COMPLEXITY AND ROBUSTNESS

A given code may be more, or less, robust to varying modes of operation. For example, the implementation loss when 8 bits of quantization are used for the channel symbols would be different than when 3 bits were used, or 1 bit (hard decision). A code whose implementation loss profile is more gradual would be more robust and applicable to severely constrained missions that for complexity/mass reasons may not be able to implement the full standard decoder.

It is important to recognize that there is a tradeoff in receiver complexity vs. how much power is assigned to the carrier (mod index). Simpler receivers need more carrier power to acquire, and, since the coding gain relates only to the power in the data (not in the carrier), the effective coding gain may be reduced. This effect may be prevalent at very low data rates, unless the receiver is improved. Also the receiver must be able to do symbol synchronization at lower E_b/N_0 if the coding gain is higher.

3.12 COMPATIBILITY WITH LEGACY MISSIONS

There is value in preserving compatibility with existing spacecraft. This reduces the number of distinct sets of hardware that must be maintained in a ground station.

4 APPLICATION PROFILES

4.1 OVERVIEW

Each of the five application profiles places demands on the coding system that can be paired with the FOMs just enumerated. Some of the demands are hard thresholds that must be met; others assign relative significance that can be used to rank candidate codes. In the following paragraphs, requirements are briefly described and tabulated for the first seven FOMs enumerated in 3.2.

4.2 MODE A: DEEP SPACE EMERGENCY COMMUNICATION, UNMANNED MISSIONS

Mode A, deep space emergency communication, unmanned missions, is concerned primarily with communication to an unmanned spacecraft with a fault that affects the communication system itself. Such emergency communication is necessary, for example, if a spacecraft loses attitude control or if the receiver suffers a partial failure. These situations could result in a low received power level, or a useful received power level only for short time intervals (if the spacecraft is spinning, or the symbol timing loop cannot track, for example). The uplink communications goal is to deliver a short command of about 100 bits, either at an extremely low data rate, or during a short time interval, or both. Bandwidth efficiency is not of concern. The detected error rate may be high because lost commands are expected in this situation, but an undetected error that delivers an unintended command to the spacecraft could be catastrophic. These requirements are summarized in the following table.

Application: Emergency		
Power efficiency	critical	
Required E_b/N_o	5	dB
QoS	data	
CWER	10^{-3}	
UCWER	10^{-9}	
Data Rate	8	b/s
Spectral Efficiency (bandwidth)	unconstrained	
Modulation	BPSK	
Code rate	$\leq 1/2$	
Latency	12.5	s
Block length	100	bits
Acquisition time	critical	
Frequency band	S or X	

4.3 MODE B: COMMAND/ARQ

Mode B, command and ARQ, is similar to the traditional telecommand problem addressed by the BCH code. The additional application of transmitting responses for a telemetry downlink ARQ protocol should be noted. New LDPC codes are 3 dB more power efficient than the current BCH code. As with Mode A, bandwidth efficiency is not of concern, but an undetected error that delivers an unintended command to the spacecraft could be catastrophic.

Application: Command / ARQ			
Power efficiency		good	
	Required E_b/N_o	4	dB
QoS		data	
	CWER	10^{-3}	
	UCWER	10^{-9}	
Data Rate		1–4	kb/s
Spectral Efficiency (bandwidth)		unconstrained	
	Modulation	BPSK	
	Code rate	$\leq 1/2$	
Latency		< 1	s
	Block length	0.1–1	kb
Acquisition time		important	
Frequency band		S or X	

4.4 MODE C: FILE UPLOAD

Mode C, file upload, is intended for a reprogrammable spacecraft or spacecraft instruments. One may wish to transmit software modifications or firmware changes when FPGAs or programmable ASICs are used. Bandwidth efficiency may be of concern for large file transfers. Undetected errors are likely to be detected at a higher protocol level, such as with a checksum over an entire file. Higher order modulation, i.e., QPSK is preferred for data rates above 2 Mb/s (currently met using BPSK).

Application: File Upload			
Power efficiency		good	
	Required E_b/N_o	3	dB
QoS			
	CWER	10^{-3}	
	UCWER (P_u)	10^{-6}	
Data Rate		2	Mb/s
Spectral Efficiency (bandwidth)		constrained	
	Modulation	BPSK	
	Code rate	≥ 1/2	
Latency		unconstrained	
	Block Length	1–4	kb
Acquisition time		unconstrained	
Frequency band		S, X, Ka	

4.5 MODE D: HUMAN SUPPORT

Mode D, human support, is intended for the emerging need to support astronauts in Earth orbit, at the Moon, or at Mars. Applications may include voice, video, and Internet traffic. Bandwidth efficiency will be of concern in many situations. Communications errors may cause brief disruptions in the voice or video, but are generally not of great severity. Also, checksums at higher protocol levels may protect large blocks of error-sensitive data.

Application: Human Support			
Power efficiency		good	
	Required E_b/N_o	3	dB
QoS		voice,video,data	
	CWER	10^{-3}	
	UCWER	10^{-6}	
Data Rate		20	Mb/s
Spectral Efficiency {bandwidth)		constrained	
	Modulation	≥ QPSK	
	Code rate	≥ 3/4	
Latency		< 0.2	s
	Block length	> 4	kb
Acquisition time		unconstrained	
Frequency band		X or Ka	

5 TRADE STUDIES

5.1 GENERAL

The requirements for Modes C and D are similar to each other, and similar to those for telemetry downlink. Hence, the trade study in 5.3 leads towards LDPC codes such as those selected for use in Telemetry Downlink. Requirements for Modes A and B are similar to each other, but different from those for modes C and D. The trade study in 5.2 leads toward a need for a new family of short block length LDPC codes of relatively low code rate. Mode E has been little studied so far, and remains open work.

Before embarking on the trade studies, it is worth noting that the FOMs have many interdependencies, making code selection a difficult and inexact science. Some trades can even be made for a specific code, such as that between decoder complexity and quality of service: for a given code, a simpler decoder will return a higher error rate. Other trades are more fundamental, such as that between P_w and E_b/N_o. Briefly described is Shannon's sphere packing bound that jointly constrains these parameters, and hence describes the 'playing field' for the code search for Modes A, B, C, and D. Figure 5-1 shows the sphere packing bound on E_b/N_o to achieve P_w=10^{-4}, for block lengths between 1 and 10^5 bits. Achievable regions are shown for uplink modes A, B, C, and D. The performance of several error correcting codes is shown as well. Power-efficient candidate codes appear near the bottom of each region, and this suggests that there is considerable room for improvement over the current CCSDS standard BCH code.

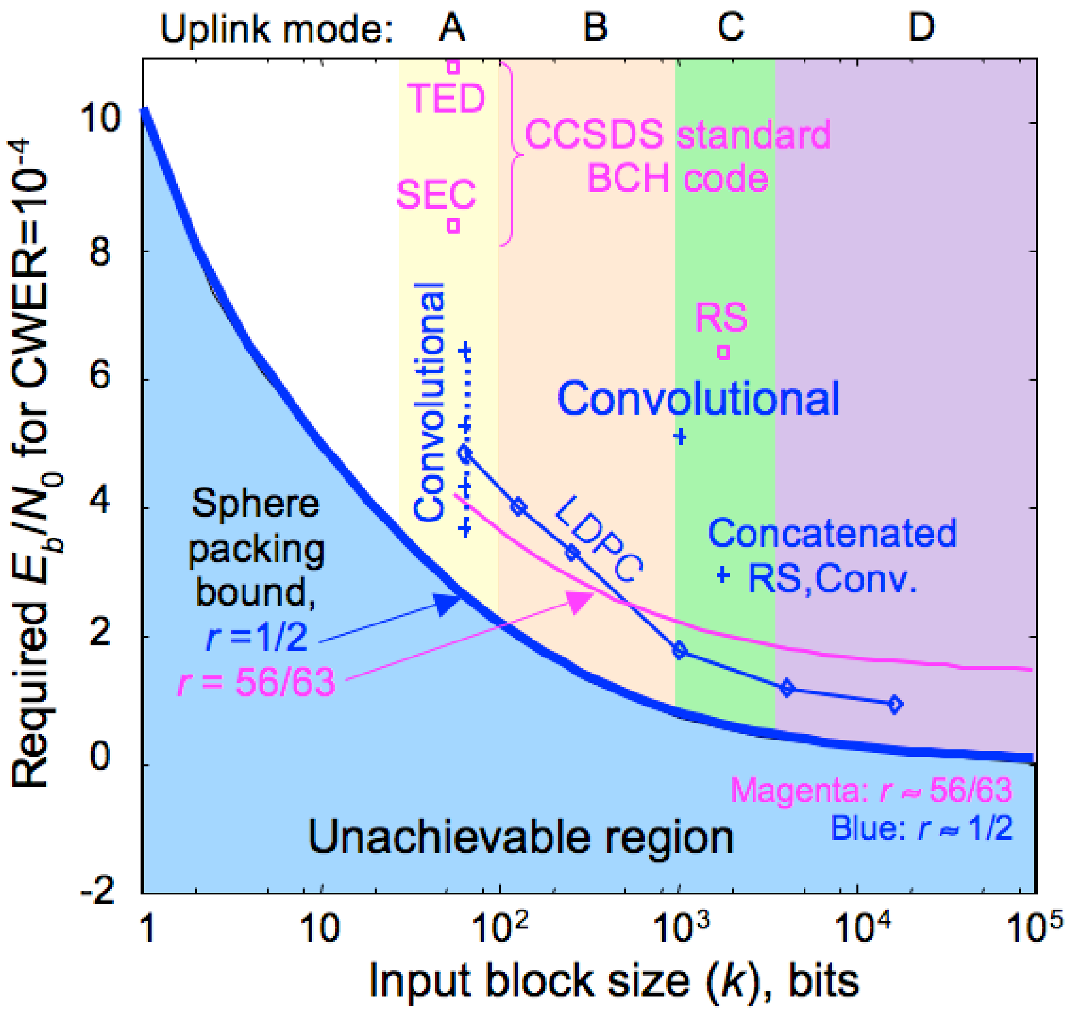

Figure 5-1: Required SNR for the Four Uplink Modes

5.2 TRADE STUDY FOR MODES A AND B

New codes for use in uplink Modes A and B must meet the performance criteria already discussed: CWER<10^{-3}, P_u<10^{-9}, and E_b/N_o as small as possible. Additional attributes include low-complexity encoders and decoders. Radio receivers that provide soft-decision outputs allow better error correction, but hard-decision outputs require less complexity, so decoders that can accept either are desirable. Radio receivers require E_b/N_o large enough to allow the symbol timing loop to track (e.g., the Electra radio requires E_b/N_o>0 dB), thus excluding modern codes with long blocklength and particularly low code rate.

Table 5-1: Code Trade Study for Modes A and B

	E_b/N_o@		Req.	Block Length		Latency	Complexity	
Code	P_w=1e−3	P_u=1e−9	E_b/N_o	n	k	(bits)	Ops/bit	Memory
Uncoded	9.4	13.4	13.4	56	56	0	0	0
BCH, SEC	7.5	9.6	9.6	63	56	56	1	0.006
BCH, TED	9.9	7.7	9.9	63	56	56	2	0.069
BCH, soft	5.7	9 (est)	9 (est)	65	56	56		
cc (3,1/2)	5.7	9.6	9.6	130	63	10	12	0.072
cc (5,1/2)	~4.7	8.11	8.11	134	63	20	48	0.45
cc (7,1/2)	3.9	7.2	7.2	138	63	40	192	2.3
cc (9,1/2)	~3.4	6.09	6.09	142	63	60	768	11.8
SEC+(3/1,2): I = 1	5.6	8.9	8.9	130	56	71	14	0.014
SEC+(3,1/2): I large	4	5.1	5.1	126I	56I	71I	14	0.014I
SEC+(7,1/2): I = 1	4.4	7.7	7.7	138	56	89	215	2.2
SEC+(7,1/2): I large	4	5.1	5.1	126I	56I	89I	215	2.2I
TED+(3,1/2): I = 1	6.2	7.6	7.6	130	56	71	15	0.079
TED+(3,1/2): I large	6.5	4.8	6.5	126I	56I	711	15	0.079I
TED+(7,1/2): I = 1	4.4	6.7	6.7	138	56	89	216	2.3
TED+(7,1/2): I large	5.3	4.1	5.3	126I	56I	89I	216	2.3I
(128,64) LDPC, 32 its	4.2	5.3	5.3	128	64	96	248 ave.	8.2
(256,128) LDPC, 32 its	3.5	1?	3.5	256	128	192		
(512,256) LDPC, 32 its	3	N/A	3	512	256	384		
(128,64) SCCC, 32 its	~3.6	6.5	6.5	128	64	96	290 ave.	7.2

A trade study of several candidate codes was performed, with results shown in table 5-1. Included is the uncoded case for reference, the existing BCH code with three decoders: SEC and TED as described in 2.2, and estimated performance of a soft-decision decoder. Also shown are two rate-1/2 convolutional codes, either alone or concatenated with the BCH code. When concatenated, the convolutional code may be terminated at the end of each BCH codeblock (I = 1), or an interleaver that interleaves a large number of BCH codewords may be used. Next, three short blocklength rate-1/2 LDPC codes are shown. Finally, a short Serially Concatenated Convolutional Code (SCCC) is shown. The required SNRs to achieve the two error-rate requirements are listed; the larger of the two is the constraining parameter and is repeated in the fourth column. The codes' block lengths n and dimensions k (or uncoded block lengths) are listed next. Their ratio gives the code rate, which is not of particular interest in Modes A and B because bandwidth is not constrained. The dimension k is the primary determinant of latency, though enough variations exist for short codes that latency is also listed separately. Finally, two measures of complexity are listed: computational operations per bit, and memory required in the decoder. The 'Memory' column gives the number of kilobits of storage required to decode the listed code; e.g., a

BCH decoder in SEC mode requires only a 6-bit shift register, and so its memory is listed as 0.006 kb.

In this table, the LDPC codes have among the lowest SNR requirements of any codes. They achieve this with higher code rates than most of the other candidates, and shorter block lengths. The performance figures in table 5-1 were generated with a maximum number of iterations set to 100. In exchange, their decoders are more complex than many of the others, but this is not an important metric in these low-data-rate modes. Based on this and other studies, the LDPC codes are considered the strongest candidates.

5.3 TRADE STUDY FOR MODES C AND D

5.3.1 GENERAL

For file upload, and human support uplink applications, much longer codes would be appropriate, and could be identical to those specified in the downlink coding and synchronization standard.

Codes for use in uplink Modes C and D must meet the performance criteria already discussed: CWER<10^{-3}, P_u<10^{-6}. Bandwidth in these modes is constrained or very constrained because the data rates are high. The remaining metrics do not have hard thresholds, but, as always, it is desirable for E_b/N_0 to be as small as possible and to support high data rates with decoders of modest complexity. Implications are that codeword lengths should be long, and QPSK and higher order modulations should be used if data rates greater than 2 Mb/s are to be achieved. Similar applications were recently addressed within the Telemetry and Synchronization Working Group, and JPL constructed the following lists of requirements, desired properties, and evaluation criteria at that time.

5.3.2 REQUIREMENTS

5.3.2.1 Code Rates: The code family shall include at least one low-rate code and one high-rate code. The former shall have rate 1/2, and the latter shall be one of the following: 3/4, 4/5, 5/6, 6/7, or 7/8. These rates shall be exact.

5.3.2.2 Block Lengths: The code family shall include block lengths covering a range from approximately k=1000 to approximately k=16,000, in intervals spaced approximately by multiples of 4. The values of k shall be divisible by 32. Codes of different rates shall have identical values of k.

5.3.2.3 Family: A single hardware implementation shall be practical and appropriate for decoding all of the codes proposed. Similarly, a single hardware implementation shall be practical and appropriate for encoding all of the codes proposed.

5.3.2.4 Intellectual property: There must be no restrictions upon use of the codes by the CCSDS member agencies.

5.3.3 DESIRED PROPERTIES

5.3.3.1 Systematic encoders: Systematic encoders are preferred. It is desirable that the information bits appear in order and as consecutive code symbols.

5.3.3.2 Code Rates: It is desired that one or two intermediate code rates be provided, in addition to the two required above.

5.3.4 EVALUATION CRITERIA

5.3.4.1 Decoder computation: Codes with smaller IE/n are preferred, where I is the average number of decoder iterations, E is the number of edges in the graph, and n is the number of channel symbols.

5.3.4.2 Encoder computation: Preferred encoders have implementations that can achieve a larger number of encoded-symbols/clock-cycle/logic-gate.

5.3.4.3 Descriptional complexity: A shorter standards document describing encoders for the codes is preferred. That is, a better code family requires fewer tables of integers to specify the code, and fewer processing steps to encode.

5.3.4.4 Code performance: Codes requiring a smaller E_b/N_o for a given CWER are preferred. Codes will be compared at CWERs of 10^{-4} and 10^{-6}.

5.3.5 SELECTION METHODOLOGY

Recognizing that when a code family performs better in one of these categories, it generally performs worse in another, final selection was based upon the family's joint performance in all criteria. Long blocklength LDPC codes emerged as the strongest candidates.

6 RANDOMIZATION

6.1 INTRODUCTION

6.1.1 In order to maintain bit (or symbol) synchronization with the received communications signal, for every data capture system at the receiving end the incoming signal must have a minimum bit transition density (see section 5 in reference [2]).

6.1.2 In order to ensure proper receiver operation, the data stream must be sufficiently random. The Pseudo-Randomizer defined in reference [2] is the preferred method to ensure sufficient randomness for all combinations of CCSDS-recommended modulation and coding schemes. The Pseudo-Randomizer defined in reference [2] is required.

6.1.3 A random sequence is exclusively ORed with the Transfer Frame(s) to increase the frequency of bit transitions. On the receiving end, the same random sequence is exclusively ORed with the data, restoring the original data. The random sequence is generated by the Bit Transition Generator (BTG).

6.2 RANDOMIZER DESCRIPTION

The random sequence is the same as defined in TC Sync and Channel Coding [2].

6.3 APPLICATION OF THE RANDOMIZER

6.3.1 GENERAL

The random sequence to be used in all cases below is defined in reference [2]. The random sequence is generated by the BTG.

6.3.2 FOR BCH ENCODED TRANSFER FRAMES

6.3.2.1 For the BCH encoded case, the following recommendation copied and modified from reference [2] applies: ‘the randomization shall be applied at the transmitting end, and it shall be applied only to the Transfer Frame(s). The BTG shall be preset to the ‘all-ones’ state at the start of Transfer Frame and then shall be exclusively ORed, bit by bit, with the Transfer Frame until the process ends with the last bit of the Transfer Frame to be transmitted in a CLTU.’ The randomization may also be applied to the fill data added after the end of the Transfer Frame to complete the last codeblock of the CLTU, but doing so is optional.

6.3.2.2 It is recommended that the CLTU be limited to one and only one Transfer Frame, since no agency has a case to defend multiple TC frames per CLTU. It is also recommended that randomization be mandatory and that fill data mentioned above, if present, also be randomized.

6.3.2.3 For the BCH encoded case, at the receiving end, the derandomization shall be applied to the successfully decoded data. The BTG shall remain in the 'all-ones' state until the CLTU Start Sequence has been detected. The BTG pattern shall be exclusively ORed, bit by bit, to the successfully decoded data (after the Error Control Bits have been removed). The BTG shall be reset to the 'all-ones' state following a failure of the decoder to decode a BCH codeblock successfully or other loss of data.

6.3.3 FOR LDPC ENCODED TRANSFER FRAMES

6.3.3.1 For the LDPC encoded case, the order in which randomization and encoding occurs differs from the BCH case as follows: the randomization shall be applied at the transmitting end **after** LDPC encoding, and it shall be applied only to the transfer frame. The randomization shall also be applied to the fill data added after the end of the Transfer Frame to complete the last codeblock of the CLTU.

NOTE – Randomization is required for LDPC decoding. If an LDPC codeword is incorrectly synchronized by a few symbols and the TC frame data is not sufficiently randomized, then the LDPC decoder may be prone to make undetected decoding errors. Randomizing the LDPC codeword(s) mitigates this risk.

6.3.3.2 For the LDPC encoded case, at the receiving end, the derandomization shall be applied immediately after synchronization is detected. The BTG shall remain in the 'all-ones' state until the CLTU Start Sequence has been detected. The BTG pattern shall be exclusively ORed, bit by bit, to the successfully synchronized data. The BTG shall be reset to the 'all-ones' state following a failure of the synchronizer to successfully obtain synchronization.

ANNEX A

ABBREVIATIONS AND ACRONYMS

ARQ	automatic repeat request
ASIC	application specific integrated circuit
BER	bit error rate
BPSK	binary phase shift keying
BTG	bit transition generator
CFDP	CCSDS File Delivery Protocol
CLCW	communications link control word
CLTU	command link transmission unit
CRC	cyclic redundancy check
CSTS	Cross Support Transfer Services
CWER	code word error rate
DSN	Deep Space Network
DTN	Delay/Disruption Tolerant Networking
E_b/N_o	bit-energy-to-noise ratio (see SNR)
EIRP	effective isotropic radiated power
FEC	forward error correction
FER	frame error rate
FOM	figure of merit
FPGA	field programmable gate array
IOAG	Interagency Operations Advisory Group
LDPC	low density parity check
LDPCC	LDPC code
LTP	Licklider Transmission Protocol

MSPA	multiple spacecraft per antenna
NAK	negative acknowledgement
NGU	Next Generation Uplink
OSI	Open Systems Interconnection
PCM	pulse code modulation
PDU	protocol data unit
PROX-1	Proximity-1
PSK	phase shift keying
QoS	quality of service
QPSK	quadrature phase shift keying
SCCC	serially concatenated convolutional code
SDU	service data unit
SEC	single-error-correction
SLE	Space Link Extension
SNR	signal-to-noise ratio
TED	triple-error-detection
TRL	technology readiness level
UCWER	undetected code word error rate
WER	word error rate