Proposed update to 131.0-B-3 TM Synchronization and Channel Coding

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Government sponsorship acknowledged.

Objective

Update 131.0-B-3, “TM Synchronization and Channel Coding” Blue Book to allow ground-to-space links, and to add USLP support.

Updates for which we have consensus

Add Ground-to-Space Links

- Add a short Section 9 to permit use of a subset of the codes for ground-to-space and space-to-space links
- That subset includes LDPC codes, and excludes RS and convolutional codes. We have not agreed about turbo codes.

Add Unified Space Data Link Protocol

- Prior references to “TM or AOS” are modified to “TM, AOS, or USLP”

Updates for which we still need to reach consensus

Do we allow turbo codes on uplinks and cross-links?

- See following slides for an argument in favor.

Do we change the name of the book?

- **Option 1:** No change. Keep the title, “TM Synchronization and Channel Coding”
    - This is familiar. It avoids renaming the companion Green Book, and updating references in many CCSDS and non-CCSDS documents.

- **Option 2:** Change the name to
  a) “Convolutional, Reed-Solomon, Turbo, and LDPC Channel Coding”
  b) “Telemetry Channel Coding”
  c) Something else?

  Goals:
    - Pick something descriptive, and distinct from the other coding Blue Books
    - Eliminate confusion between the “TM Coding” and “TM Space Link Protocols” Blue Books.
    - Eliminate apparent pairing between “TM Coding” and “TC Coding” standards.

In this presentation, I have chosen to keep the existing name for lack of a better suggestion.

New updates

Added a cautionary note about turbo codes on a ground-to-space link:

NOTE – When a low-rate turbo code (particularly 1/4 or 1/6) is used near its decoding threshold, the symbol SNR may be below -5 dB. The radio receiver’s symbol tracking loop may require an uncommonly narrow loop bandwidth, and an external means for Doppler compensation.

A Case for Turbo Codes

Scenario 1: 30 Mbps uplink to a human Mars mission

Ka band, 30 Mbps, 6m S/C antenna, 34m BWG, 1kW transmit power, 20 degree elevation angle, Turbo (8920,1/6)

Scenario 2: HDTV to the Moon

Human-transportable antenna on the Moon from a 4 meter ground antenna

Non-scenario 3: Uplinks to Low Earth Orbit

Power does not appear to be a constraint for any reasonable forward link to LEO, and so turbo codes are not applicable.

Scenario 1: 30 Mbps uplink to a human Mars mission

This case is NASA/JPL’s primary motivation for requesting turbo codes on a ground-to-space link

Objectives:

- 30 Mbps data rate for ground-to-space
- Mars max range (2.5 AU)
- ~1.5 kW Ka-band transmitter (trade study ongoing)
- 34-meter BWG transmit antenna
- 6-meter spacecraft antenna

With the (8920,1/6) turbo code, this link is just about possible (depending on assumed losses, transmitter power, etc.)

With rate-1/2 LDPC codes or above, it is not possible.

Scenario 1: 30 Mbps uplink to a human Mars mission

UPLINK						
			INPUTS			
Transmit power	61.76	dBm	1.5	kWatts		
			34.25	GHz	Frequency	Ka up
Ground antenna	80.55	dbi	34	meters	Antenna diameter	
				0.008759124	wavelength, meters	
				0.000257621	beam width, radians	
			0.6		Efficiency	
				113605037.8	Antenna gain	
Space loss	-295.20	dB	4.01E+08	km	Range	Mars max range
Flight antenna	61.13	dBi	6	meters	Antenna diameter	
				0.001459854	beam width, radians	
				0.083643474	beam width, degrees	
			0.22		Efficiency	
				1297220.155	Antenna gain	
	-3.40	dB	-3.4		Receiver losses, etc.	
Received power, Pt	-95.15	dBm				
Noise spec dens, No	-172.59	dBm	399.17	K	Noise temp	
Pt/No	77.43	dB		1.38E-23	Boltzmann	
Carrier supp.	-15.20		-15.2	dB	Mod index = 80 deg	
Loop bandwidth	20.49		112	Hz		
Required loop SNR	12.00		12	dB	SDST	
CARRIER MARGIN	29.74					
Modulation supp.	-0.13	dB	-0.13	dB	Mod index = 80 deg	
Data rate	74.77		30000	kbps		
System loss	-0.84	dB	-0.84	dB	Radio losses, etc.	
Coding threshold	-0.20	dB	-0.2	Eb/No	Coding	Turbo (8920,1/6)
DATA MARGIN	1.89	dB				

Link is just possible with turbo codes

Scenario 2: HDTV to a transportable antenna on the Moon

This is just a concept to explore what's possible

Objectives:

- **50 Mbps for HDTV to a transportable antenna on the Moon**
- **Earth antenna: 4 meter, 100W, Ka-band**
- **Transportable lunar antenna: 0.5 meter parabolic**
- **Range: 384,000 km**

This link is about possible with the (1784,1/3) turbo code, again depending on assumed losses, desired margin, etc.

With rate-1/2 LDPC codes or above, it is difficult or impossible.

Scenario 2: 50 Mbps HDTV to the Moon

UPLINK						
			INPUTS			
Transmit power	50.00	dBm	0.1	kWatts		
			34.25	GHz	Frequency	Ka up
Ground antenna	61.97	dbi	4	meters	Antenna diameter	
				0.008759124	wavelength, meters	
				0.002189781	beam width, radians	
			0.6		Efficiency	
				1572388.067	Antenna gain	
Space loss	-234.83	dB	3.84E+05	km	Range	Mars max range
Flight antenna	39.55	dBi	0.5	meters	Antenna diameter	
				0.017518248	beam width, radians	
				1.003721685	beam width, degrees	
			0.22		Efficiency	
				9008.473301	Antenna gain	
	-6.00	dB	-6		Receiver losses, etc.	
Received power, Pt	-89.32	dBm				
Noise spec dens, No	-171.61	dBm	500	K	Noise temp	
Pt/No	82.29	dB		1.38E-23	Boltzmann	
Carrier supp.	-15.20		-15.2	dB	Mod index = 80 deg	
Loop bandwidth	20.49		112	Hz		
Required loop SNR	12.00		12	dB	SDST	
CARRIER MARGIN	34.60					
Modulation supp.	-0.13	dB	-0.13	dB	Mod index = 80 deg	
Data rate	76.99		50000	kbps		
System loss	-0.84	dB	-0.84	dB	Radio losses, etc.	
Coding threshold	0.80	dB	0.8	Eb/No	Coding	Turbo (1784,1/3)
DATA MARGIN	3.53	dB				

Link is possible with a short rate-1/3 turbo code

The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

TM SYNCHRONIZATION AND CHANNEL CODING

RECOMMENDED STANDARD

CCSDS 131.0-B-4?

BLUE BOOK

May 2021

1 INTRODUCTION

1.1 PURPOSE

The purpose of this Recommended Standard is to specify synchronization and channel coding schemes used with the TM Space Data Link Protocol (reference [1]), the AOS Space Data Link Protocol (reference [2]), or the Unified Space Data Link Protocol (USLP, reference [6]). These schemes are to be used over space-to-ground, space-to-space, or ground-to-space communications links by space missions.

1.5 DOCUMENT STRUCTURE

This document is divided into thirteen numbered sections and seven annexes:

a) section 1 presents the purpose, scope, applicability and rationale of this Recommended Standard and lists the conventions, definitions, and references used throughout the document;

b) section 2 provides an overview of synchronization and channel coding;

c) section 3 specifies convolutional coding;

d) section 4 specifies Reed-Solomon coding;

e) section 5 concatenated coding;

f) section 6 specifies Turbo coding;

g) section 7 specifies low-density parity-check coding of a Transfer Frame;

h) section 8 specifies low-density parity-check coding of a stream of Sync-Marked Transfer Frames (SMTFs);

i) section 9 specifies use of these codes for forward links (ground to space or space to space);

j) section 10 specifies the frame synchronization scheme;

k) section 11 specifies the Pseudo-Randomizer;

l) section 12 specifies the allowed lengths of Transfer Frames;

m) section 13 lists the managed parameters associated with synchronization and channel coding;

n) annex A defines the service provided to the users;

o) annex B discusses security issues related to TM Channel Coding;

p) annex C provides the generator matrix circulant table applicable to rate-223/255 LDPC coding (see 7.3);

q) annex D lists acronyms and terms used within this document;

r) annex E provides a list of informative references;

s) annex F provides information on transformation between the Berlekamp (dual basis) and Conventional representations;

t) annex G provides information on Reed-Solomon coefficients.

1.8 REFERENCES

[6] *Unified Space Data Link Protocol*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.1-B-1. Washington, D.C.: CCSDS, October 2018.

2 OVERVIEW

2.1 ARCHITECTURE

Figure 2-1 illustrates the relationship of this Recommended Standard to the Open Systems Interconnection reference model (reference [3]). Two sublayers of the Data Link Layer are defined for CCSDS space link protocols. The TM, AOS, and USLP Space Data Link Protocols specified in references [1], [2], and [6], respectively, correspond to the Data Link Protocol Sublayer, and provide functions for transferring data using the protocol data unit called the Transfer Frame. The Synchronization and Channel Coding Sublayer provides additional functions necessary for transferring Transfer Frames over a space link. These functions are error-control coding/decoding, Transfer Frame delimiting/synchronizing, and bit transition generation/removal.

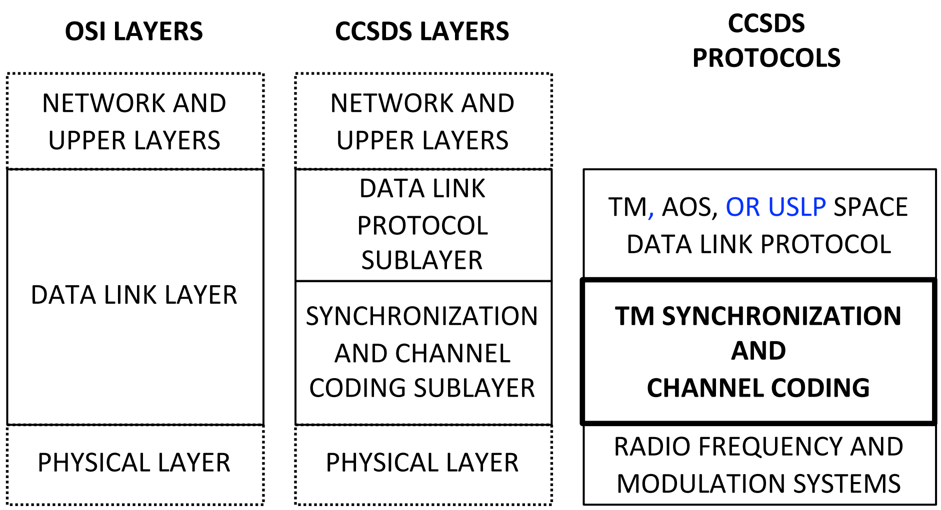

Figure 2-1: Relationship with OSI Layers

2.2 SUMMARY OF FUNCTIONS

2.2.1 GENERAL

The Synchronization and Channel Coding Sublayer provides the following three functions for transferring Transfer Frames over a space link:

a) error-control coding, including frame validation;

b) synchronization; and

c) pseudo-randomizing.

2.2.2 ERROR-CONTROL CODING

This Recommended Standard specifies the following four types of error-control coding:

a) convolutional coding (section 3);

b) Reed-Solomon coding (section 4);

c) Turbo coding (section 5);

d) Low-Density Parity-Check (LDPC) coding (sections 7 and 8).

One of the convolutional codes described in section 3 alone may be satisfactory depending on performance requirements.

For Physical Channels, which are bandwidth-constrained and cannot tolerate the increase in bandwidth required by the basic convolutional code specified in 3.3, the punctured convolutional codes specified in 3.4 have the advantage of smaller bandwidth expansion.

Alternatively, the Reed-Solomon codes and the high rate LDPC code specified in sections 4, 7, and 8 also have the advantage of smaller bandwidth expansion and have the capability to indicate the presence of uncorrectable errors. Where a greater coding gain is needed than can be provided by a convolutional code or Reed-Solomon code alone, a concatenation of a convolutional code as the inner code with a Reed-Solomon code as the outer code may be used for improved performance.

The Turbo codes specified in section 5 or the LDPC codes specified in sections 7 and 8 may be used to obtain even greater coding gain where the environment permits.

The AOS and USLP data link layer protocols are symmetrical and may be used in return, cross-link, or forward directions.

NOTES

1 In this Recommended Standard, the characteristics of the codes are specified only to the extent necessary to ensure interoperability and cross-support. The specification does not attempt to quantify the relative coding gain or the merits of each approach discussed, nor does it specify the design requirements for encoders or decoders.

2 The domains of applicability for the codes specified in this document are delineated in *Mission Profiles for TM Synchronization and Channel Coding* (reference [E5]).

3 CONVOLUTIONAL CODING

3.2 GENERAL

3.2.3 FRAME VALIDATION

When TM, AOS, or USLP Transfer Frames are used, the Frame Error Control Field (FECF) specified in references [1], [2], or [6] shall be used to validate the Transfer Frame, unless the convolutional code is concatenated with an outer Reed-Solomon code (see section 4).

NOTE – If the decoder's correction capability is exceeded, undetected bursts of errors may appear in the output.

4 REED-SOLOMON CODING

4.2 GENERAL

4.2.2 FRAME VALIDATION

The FECF specified in references [1], [2], or [6] is optional. The system designer may choose to use it for additional codeblock validation, particularly with the E=8 code.

NOTE – The Reed-Solomon code with E=16 has an extremely low undetected error rate, and that with E=8 has an undetected error rate low enough for some applications. Therefore the R-S decoder may be used alone to validate the codeblock, and consequently the contained TM Transfer Frame (reference [1]), AOS Transfer Frame (reference [2]), or USLP Transfer Frame (reference [6]).

4.3 SPECIFICATION

4.3.8 REED-SOLOMON CODEBLOCK PARTITIONING AND VIRTUAL FILL

4.3.8.1 Parts of the partitioned Reed-Solomon codeblock (see figure 4-1) are defined as follows:

a) The **Reed-Solomon Check Symbols** shall consist of the trailing $2EI$ symbols ($2EIJ$ bits) of the codeblock.

NOTES

1 As an example, when E = 16 and k = 223, for I=5 this is always 1280 bits.

2 The **Transfer Frame** is defined by the TM Space Data Link Protocol (reference [1]), the AOS Space Data Link Protocol (reference [2]), or the Unified Space Data Link Protocol (reference [6]). For constraints on the length of the Transfer Frame, see section 12.

b) The **Attached Sync Marker** used with R-S code

1) shall be the 32-bit pattern specified in section 10;

2) shall precede the transmitted codeblock.

NOTE – Frame synchronizers should therefore be set to expect a marker at every transmitted codeblock + 32 bits.

c) The **transmitted codeblock** shall consist of the Transfer Frame (without the 32-bit sync marker) and R-S check symbols.

6 TURBO CODING

6.2 GENERAL

6.2.2 FRAME VALIDATION

When Turbo codes are used with TM, AOS, or USLP Transfer Frames, the FECF specified in references [1], [2], or [6], respectively, shall be used to validate the Transfer Frame.

NOTE – The Reed-Solomon code with E=16 has an extremely low undetected error rate, and that with E=8 has an undetected error rate low enough for some applications. Therefore the R-S decoder may be used alone to validate the codeblock, and consequently the contained TM Transfer Frame (reference [1]), AOS Transfer Frame (reference [2]), or USLP Transfer Frame (reference [6]).

7 LOW-DENSITY PARITY-CHECK CODING OF A TRANSFER FRAME

7.2 GENERAL

7.2.3 FRAME VALIDATION

7.2.3.1 The LDPC decoder may be used alone to validate the codeword, and consequently the contained TM Transfer Frame (reference 1), AOS Transfer Frame (reference [2]), or USLP Transfer Frame (reference [6]).

7.2.3.2 The FECF specified in references [1], [2], and [6] is optional, and the system designer may choose to use it for additional frame validation.

NOTE – The undetected frame and bit error rates of these LDPC codes lie several orders of magnitude below the corresponding detected error rates for any given operating signal-to-noise ratio.

8 LOW-DENSITY PARITY-CHECK CODING OF A STREAM OF SYNC-MARKED TRANSFER FRAMES

8.2 GENERAL

8.2.1 SYNCHRONIZATION

[Note to editor: the previous two headings appear to have been confused in the currently published book]

8.2.2 CSM BIT PATTERNS

8.2.3 FRAME VALIDATION

The LDPC decoder may be used alone to validate the codeword, and consequently the contained TM Transfer Frame(s) (reference [1]), AOS Transfer Frame(s) (reference [2]), or USLP Transfer Frame(s) (reference [6]). Whenever an LDPC codeword fails decoding, the Quality Indicator (see annex A) of all the Transfer Frames affected by that decoding shall be set to show that there is an uncorrectable error in received Transfer Frame(s).

NOTE – The FECF specified in references [1], [2], and [6] is optional, and the system designer may choose to use it for additional checks.

9 USE OF TELECOMMUNICATIONS CHANNEL CODES FOR FORWARD LINKS (GROUND TO SPACE OR SPACE TO SPACE)

9.1 OVERVIEW

The error control codes specified in this document are designed for use with fixed length space data link Transfer Frames as defined in the TM Space Data Link Protocol (reference [1]), AOS Space Data Link Protocol (reference [2]), or Unified Space Data Link Protocol (reference [6]). The AOS and USLP protocols are defined for Telemetry (downlink) use, as is TM, but AOS and USLP are also designed for use for ground-to-space and space-to-space communications. This use will typically be adopted for high rate missions, missions where the forward and return links are symmetric, or for missions that are adopting upper layer networking protocols like DTN or IP.

9.2 FORWARD LINK TURBO CODES

Turbo codes are best suited to power-constrained links, where the signal to noise ratio, E_b/N_0, is a dominant concern. Their code rates of $r \leq 1/2$ provide greater coding gain than LDPC codes, at a cost of greater bandwidth expansion. They are best suited to links beyond low-Earth orbit.

9.3.1 For AOS or USLP forward links, any of the turbo codes in section 6 shall be selected. They offer code rates of $r = 1/2$, 1/3, 1/4, and 1/6, and block lengths of 1784, 3568, 7136, and 8920 information bits.

NOTE – When a low-rate turbo code (particularly 1/4 or 1/6) is used near its decoding threshold, the symbol SNR may be below -5 dB. The radio receiver's symbol tracking loop may require an uncommonly narrow loop bandwidth, and an external means for Doppler compensation.

9.3 FORWARD LINK LOW-DENSITY PARITY-CHECK CODES

LDPC codes are best suited to high data-rate links, due to their code rates of $r \geq 1/2$, and the potentially parallel implementation architecture for the decoder. They are best suited to links where bandwidth is limited, onboard computational resources are available to support an iterative decoder, and with a physical-layer modulation that supports at least two code symbols per modulation symbol (QPSK/OQPSK and above).

9.4.1 For AOS or USLP forward links, any of the LDPC codes in section 7 shall be selected. They offer code rates of r=1/2, 2/3, 4/5, and approximately 7/8. Block lengths of 1024, 4096, and 16384 information bits are available with the first three code rates; and 7136 information bits in the last case.

9.4 FORWARD LINK CODING OF A STREAM OF SYNC-MARKED TRANSFER FRAMES

In some cases, it is most practical to use a Transfer Frame length that need not match the information block length of the error correcting code. To support this application, synchronization markers may be prepended to the Transfer Frames, the resulting Synchronization Marked Transfer Frames (SMTFs) concatenated into a stream, and then “sliced” according to the information block length of the code.

9.5.1 When a stream of Synchronization Marked Transfer Frames is chosen for an AOS or USLP forward link, the encoding procedure defined in Section 8 shall be selected.

11 TRANSFER FRAME LENGTHS

11.1 OVERVIEW

Neither the TM Space Data Link Protocol (reference [1]) nor the AOS Space Data Link Protocol (reference [2]) specifies the length of Transfer Frames because there are constraints on the Transfer Frame length depending on the selected coding options.

The Unified Space Data Link Protocol (reference [6]) contains a frame length field that is specified by the sender for both fixed or variable length transfer frames. In the variable length case, the maximum frame size is constrained by the size of the frame length field.

The constraints on Transfer Frame lengths specified in this section apply to TM Transfer Frames, AOS Transfer Frames, and USLP Transfer Frames (when fixed length transfer frames are used).

ANNEX A

SERVICE

(NORMATIVE)

A2 OVERVIEW OF THE SERVICE

Convolutional, Reed-Solomon, Turbo, and LDPC Channel Coding provides unidirectional (one way) transfer of a sequence of fixed-length TM, AOS, or USLP Transfer Frames at a constant frame rate over a Physical Channel across a space link, with optional error detection/correction.

Only one user can use this service on a Physical Channel.

A3 SERVICE PARAMETERS

A3.1 FRAME

A3.1.1 The Frame parameter is the service data unit of this service and shall be either a TM Transfer Frame defined in reference [1], an AOS Transfer Frame defined in reference [2], or a USLP Transfer Frame defined in reference [6].

ANNEX D

ACRONYMS AND TERMS

(INFORMATIVE)

D1 INTRODUCTION

This annex lists key acronyms and terms that are used throughout this Recommended Standard to describe synchronization and channel coding.

D2 ACRONYMS

USLP	Unified Space Link Protocol

BACKUP

The Politics

As many working group members are aware, there have been political issues at the CESG and CMC levels.

In discussions over the past few months, a consensus was reached:

1. The updated DVB-S2 Blue Book will be unblocked, and released for Agency Review
2. When submitted, an updated SCCC Blue Book will not be blocked from Agency Review
3. SCCC-X and DVB-S2X Orange Books may be revised and submitted for publication
4. The C&S Working Group is expected to reach consensus on updates to the "TM Coding" Blue Book at the Spring meeting, and submit it for Agency Review.

This compromise is documented in the "Liberal Approach" memo, following.

CESG Chair: Klaus-Juergen Schulz, Margherita di Giulio (transitioning)
CESG Deputy Chair: Wallace Tai, Timothy Pham (proposed)
SEA Chair: Peter Shames
SLS Chair: Gian Paolo Calzolari
SLS Deputy Chair: Gilles Moury
SLS-C&S Chair: Andrea Modenini (proposed)
SLS-C&S Deputy Chair: Kenneth Andrews
SLS-C&S WG Members: Victor Sank, Shannon Rodriguez

As encouraged by CMC in Dec 2020 the above persons met on 11 Feb and 11 Mar 2021 via video conference to discuss the way forward with 3 blue and 2 orange books under development by the SLS-C&S WG related to the coding and synchronisation schemes for high rate uplinks and cross links (i.e. space to space links). The history is not recalled here. The following consensus was reached.

Record of Consensus:

In order to facilitate an expedited conclusion on coding and synchronisation schemes for high rate uplinks and cross links the SLS-C&S WG is guided to apply systematically a “liberal” approach, i.e. without consideration of applicability (Earth<->Space links, Cross links) and directionality (Space-to-Earth-links, Earth-to-Space-links, forward-cross-links, return-cross-links). This is intended to provide interoperable coding and synchronisation recommended standards for the high rate AOS and USLP link layer protocols for the designers of future space missions, as well as experimental specifications. It will remain for the engineers of specific missions to choose which recommendations to follow for their particular mission profile and application.

Based on the above consensus the following was agreed:

1. CCSDS 131.3-P-1.1, CCSDS Space Link Protocols over ETSI DVB-S2 Standard (Pink Sheets, Issue 1.1); will be released for CCSDS Agency review, in this review process the “liberal” approach will be followed
2. CCSDS 131.0-B-3, TM Synchronisation and Channel Coding; will be updated following the “liberal” approach and then submitted to CESG+CMC Polls to start Agency Review
3. CCSDS 131.2-B-1, Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications; will be updated following the “liberal” approach and then submitted to CESG+CMC Polls to start Agency Review
4. CCSDS 131.21-O-1, SCCC Extension (SCCC-X) (Orange Book, Issue 1) will be revised following the “liberal” approach and then submitted to CMC Poll for publication
5. CCSDS 131.31-O-1, CCSDS Space Link Protocols over ETSI DVB-S2X Standard (Orange Book, Issue 1) already following the “liberal” approach will be submitted to CMC Poll for publication