The Consultative Committee for Space Data Systems

Draft Recommendation for
Space Data System Standards

TM SYNCHRONIZATION AND CHANNEL CODING

DRAFT RECOMMENDED STANDARD

CCSDS 131.0-P-1.1

PINK BOOK
November 2009

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FOREWORD

This document is a technical ~~Recommendation~~Recommended Standard for use in developing synchronization and channel coding systems and has been prepared by the Consultative Committee for Space Data Systems (CCSDS). The synchronization and channel coding concept described herein is intended for missions that are cross-supported between Agencies of the CCSDS.

This ~~Recommendation~~Recommended Standard establishes a common framework and provides a common basis for the synchronization and channel coding schemes to be used by space missions with the TM or AOS Space Data Link Protocol (references [1] or [2]) over space-to-ground and space-to-space communications links. This ~~Recommendation~~Recommended Standard was developed by consolidating the specifications regarding synchronization and channel coding in older CCSDS ~~Recommendation~~Recommended Standards (references [D2] and [D3]).

This ~~Recommendation~~Recommended Standard does not change the major technical contents defined in references [D2] and [D3], but the presentation of the specification has been changed so that:

a) these schemes can be used to transfer any data over any space link in either direction;

b) all CCSDS space link protocols are specified in a unified manner;

c) the layered model matches the Open Systems Interconnection (OSI) Basic Reference Model (reference [3]).

Together with the change in presentation, a few technical specifications in references [D2] and [D3] have been changed in order to define all Space Data Link Protocols in a unified way. Also, some technical terms in references [D2] and [D3] have been changed in order to unify the terminology used in all the CCSDS ~~Recommendation~~Recommended Standards that define space link protocols and to define these schemes as general communications schemes. These changes are listed in annex G of this ~~Recommendation~~Recommended Standard.

Through the process of normal evolution, it is expected that expansion, deletion or modification to this document may occur. This ~~Recommendation~~Recommended Standard is therefore subject to CCSDS document management and change control procedures, as defined in the *Procedures Manual for the Consultative Committee for Space Data Systems*. Current versions of CCSDS documents are maintained at the CCSDS Web site:

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PREFACE

This document is a draft CCSDS Recommended Standard. Its ‘Pink Book’ status indicates that the CCSDS believes the document to be technically mature and has released it for formal review by appropriate technical organizations. As such, its technical contents are not stable, and several iterations of it may occur in response to comments received during the review process.

Implementers are cautioned **not** to fabricate any final equipment in accordance with this document’s technical content.

DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 131.0-B-1	TM Synchronization and Channel Coding, Issue 1	September 2003	Original issue
CCSDS 131.0-P-1.1	TM Synchronization and Channel Coding, Draft Recommended Standard, Issue 1.1	November 2009	Current draft: – adds LDPC Code and Security Section; – updates other coding sections for uniformity of presentation; – corrects and updates erroneous and obsolete material (note).

NOTE – Substantive changes from the current Blue Book are indicated with change bars in the right margin.

CONTENTS

CONTENTS (continued)

Section Page

CONTENTS (continued)

CONTENTS (continued)

Figure Page

Table

1 INTRODUCTION

1.1 PURPOSE

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

1.2 SCOPE

This ~~Recommendation~~Recommended Standard defines synchronization and channel coding schemes in terms of:

a) the services provided to the users of this specification;

b) data formats; and

c) the procedures performed to generate and process the data formats.

It does not specify:

a) individual implementations or products;

b) the methods or technologies required to perform the procedures; or

c) the management activities required to configure and control the system.

1.3 APPLICABILITY

This ~~Recommendation~~Recommended Standard applies to the creation of Agency standards and to the future data communications over space links between CCSDS Agencies in cross-support situations. This ~~Recommendation~~Recommended Standard includes comprehensive specification of the data formats and procedures for inter-Agency cross support. It is neither a specification of, nor a design for, real systems that may be implemented for existing or future missions.

The ~~Recommendation~~Recommended Standard specified in this document is to be invoked through the normal standards programs of each CCSDS Agency, and is applicable to those missions for which cross support based on capabilities described in this ~~Recommendation~~Recommended Standard is anticipated. Where mandatory capabilities are clearly indicated in sections of this ~~Recommendation~~Recommended Standard, they must be implemented when this document is used as a basis for cross support. Where options are allowed or implied, implementation of these options is subject to specific bilateral cross support agreements between the Agencies involved.

1.4 RATIONALE

The CCSDS believes it is important to document the rationale underlying the recommendations chosen, so that future evaluations of proposed changes or improvements will not lose sight of previous decisions.

1.5 DOCUMENT STRUCTURE

This document is divided into ~~nine~~eleven numbered sections and ~~six~~seven annexes:

a) section 1 presents the purpose, scope, applicability and rationale of this Recommendation 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 ~~the~~ convolutional coding;

d) section 4 specifies ~~the~~ Reed-Solomon coding;

e) section 5 specifies ~~the~~ turbo coding;

f) section 6 specifies low density parity check coding;

g) section 7 specifies the frame synchronization scheme;

h) section 8 specifies the Pseudo-Randomizer;

i) section 9 specifies the allowed lengths of Transfer Frames;

j) section 10 lists the managed parameters associated with synchronization and channel coding;

k) section 11 discusses security issues related to TM Channel Coding;

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

m) annex B provides the generator matrix circulant table applicable to LDPC codes optimized for near-Earth applications (6.2);

n) annex C lists acronyms and terms used within this document;

o) annex D provides a list of informative references;

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

q) annex F provides information on Reed-Solomon coefficients;

r) annex G lists the changes from relevant previously published CCSDS ~~Recommendation~~Recommended Standards (references [D2] and [D3]).

1.6 CONVENTIONS AND DEFINITIONS

1.6.1 DEFINITIONS

1.6.1.1 Definitions from the Open System Interconnection (OSI) Basic Reference Model

This ~~Recommendation~~Recommended Standard makes use of a number of terms defined in reference [3]. The use of those terms in this ~~Recommendation~~Recommended Standard shall be understood in a generic sense; i.e., in the sense that those terms are generally applicable to any of a variety of technologies that provide for the exchange of information between real systems. Those terms are:

a) Data Link Layer;

b) Physical Layer;

c) service;

d) service data unit.

1.6.1.2 Definitions from OSI Service Definition Conventions

This ~~Recommendation~~Recommended Standard makes use of a number of terms defined in reference [4]. The use of those terms in this ~~Recommendation~~Recommended Standard shall be understood in a generic sense; i.e., in the sense that those terms are generally applicable to any of a variety of technologies that provide for the exchange of information between real systems. Those terms are:

a) indication;

b) primitive;

c) request;

d) service provider;

e) service user.

1.6.1.3 Terms Defined in This ~~Recommendation~~Recommended Standard

For the purposes of this ~~Recommendation~~Recommended Standard, the following definitions apply. Many other terms that pertain to specific items are defined in the appropriate sections.

~~**asynchronous:** not *synchronous*.~~

Mission Phase: a period of a mission during which specified communications characteristics are fixed. The transition between two consecutive mission phases may cause an interruption of the communications services.

Physical Channel: a stream of bits transferred over a space link in a single direction.

space link: a communications link between a spacecraft and its associated ground system or between two spacecraft. A space link consists of one or more Physical Channels in one or both directions.

~~**synchronous:** of or pertaining to a sequence of events occurring in a fixed time relationship (within specified tolerance) to another sequence of events.~~

1.6.2 NOMENCLATURE

The following conventions apply throughout this ~~Recommendation~~Recommended Standard:

a) the words 'shall' and 'must' imply a binding and verifiable specification;

b) the word 'should' implies an optional, but desirable, specification;

c) the word 'may' implies an optional specification;

d) the words 'is', 'are', and 'will' imply statements of fact.

1.6.3 CONVENTIONS

In this document, the following convention is used to identify each bit in an *N*-bit field. The first bit in the field to be transmitted (i.e., the most left justified when drawing a figure) is defined to be 'Bit 0', the following bit is defined to be 'Bit 1', and so on up to 'Bit *N*-1'. When the field is used to express a binary value (such as a counter), the Most Significant Bit (MSB) shall be the first transmitted bit of the field, i.e., 'Bit 0' (see figure 1-1).

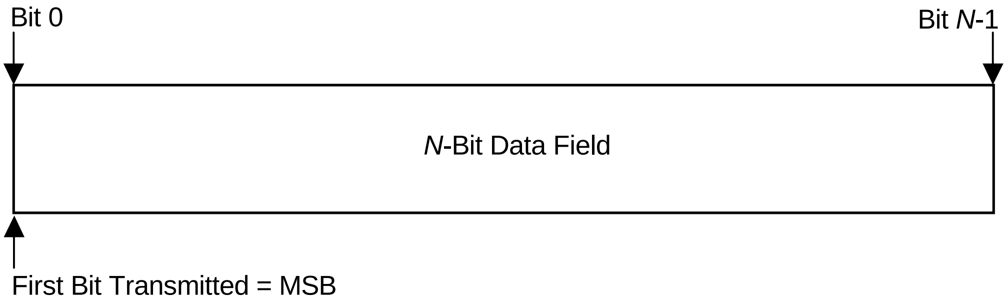


Figure 1-1: Bit Numbering Convention

In accordance with standard data-communications practice, data fields are often grouped into 8-bit 'words' which conform to the above convention. Throughout this ~~Recommendation~~Recommended Standard, such an 8-bit word is called an 'octet'.

The numbering for octets within a data structure starts with '0'.

1.7 REFERENCES

~~The following documents contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Recommendation 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 Recommendations.~~

The following documents contain provisions which, through reference in this text, constitute provisions of this Recommended Standard. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Recommended Standard 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 Recommended Standards.

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

~~[2] *AOS Space Data Link Protocol.* Recommendation for Space Data Systems Standards, CCSDS 732.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, September 2003.~~

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

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

[4] *Information Technology—Open Systems Interconnection—Basic Reference Model—Conventions for the definition of OSI services*. International Standard, ISO/IEC 10731:1994. Geneva: ISO, 1994.

[5] *Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft*. Recommendation for Space Data Systems Standards, CCSDS 401.0-B. Blue Book. Washington, D.C.: CCSDS, March 2003.

NOTE – Informative references are listed in annex D.

2 OVERVIEW

2.1 ARCHITECTURE

Figure 2-1 illustrates the relationship of this ~~Recommendation~~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 and AOS Space Data Link Protocols specified in references [1] and [2], 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.

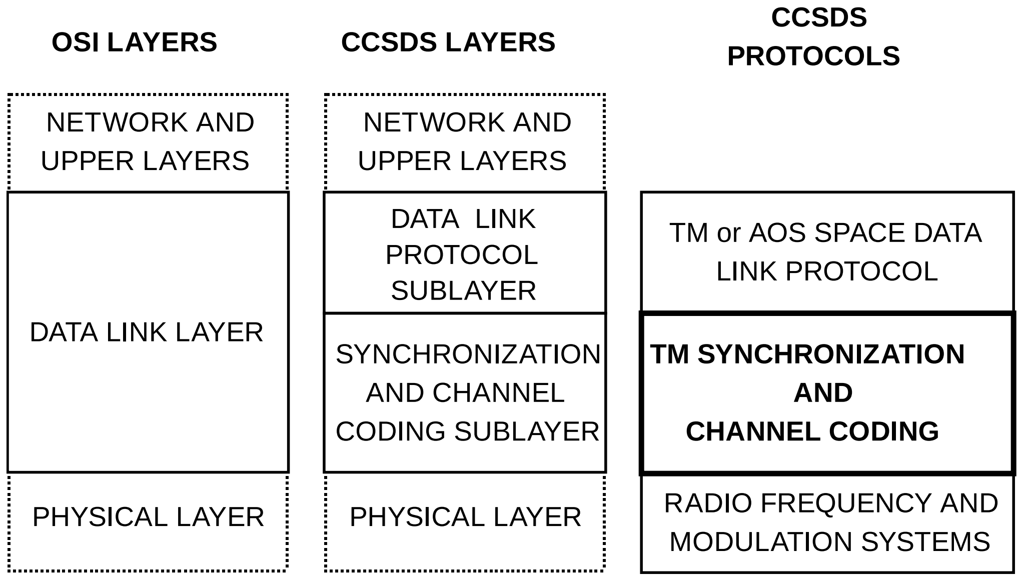

OSI LAYERS
CCSDS LAYERS
CCSDS PROTOCOLS
NETWORK AND UPPER LAYERS
NETWORK AND UPPER LAYERS
DATA LINK LAYER
DATA LINK PROTOCOL SUBLAYER
TM or AOS SPACE DATA LINK PROTOCOL
SYNCHRONIZATION AND CHANNEL CODING SUBLAYER
TM SYNCHRONIZATION AND CHANNEL CODING
PHYSICAL LAYER
PHYSICAL LAYER
RADIO FREQUENCY AND MODULATION SYSTEMS

Figure 2-1: Relationship with OSI Layers

2.2 SUMMARY OF FUNCTIONS

2.2.1 GENERAL

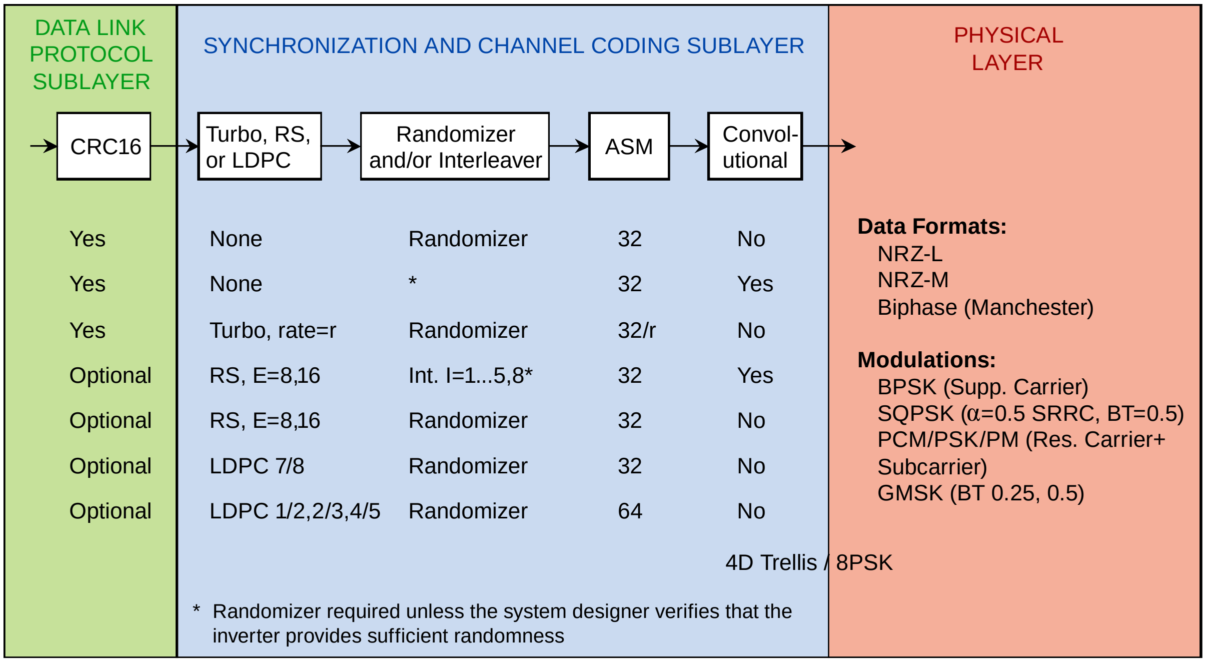
The Synchronization and Channel Coding Sublayer provides the following three functions for transferring Transfer Frames over a space link:

a) error-control coding, including frame validation~~ (optional)~~;

b) synchronization; and

c) pseudo-randomizing~~ (optional)~~.

Figure 2-2 shows examples of possible combinations of the functions above.


DATA LINK PROTOCOL SUBLAYER
SYNCHRONIZATION AND CHANNEL CODING SUBLAYER
PHYSICAL LAYER
Data Formats:
NRZ-L
NRZ-M
Biphase (Manchester)
Modulations:
BPSK (Supp. Carrier)
SQPSK (α=0.5 SRRC, BT=0.5)
PCM/PSK/PM (Res. Carrier+ Subcarrier)
GMSK (BT 0.25, 0.5)

CRC16	Turbo, RS, or LDPC	Randomizer and/or Interleaver	ASM	Convol-utional
Yes	None	Randomizer	32	No
Yes	None	*	32	Yes
Yes	Turbo, rate=r	Randomizer	32/r	No
Optional	RS, E=8,16	Int. I=1...5,8*	32	Yes
Optional	RS, E=8,16	Randomizer	32	No
Optional	LDPC 7/8	Randomizer	32	No
Optional	LDPC 1/2,2/3,4/5	Randomizer	64	No
				4D Trellis / 8PSK

* Randomizer required unless the system designer verifies that the inverter provides sufficient randomness

Figure 2-2: Combinations of Coding, Synchronization, and Pseudo-Randomizing

2.2.2 ERROR-CONTROL CODING

This ~~Recommendation~~Recommended Standard specifies the following ~~three~~four types of error-control codes:

a) convolutional codes (section 3);

b) Reed-Solomon codes (section 4);

c) turbo codes (section 5);

d) Low-Density Parity-Check (LDPC) codes (section 6).

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 ~~3.1~~section 3, the punctured convolutional code specified in 3.3 has the advantage of smaller bandwidth expansion.

For Physical Channels which are bandwidth-constrained and cannot tolerate the increase in bandwidth required by the convolutional codes, the Reed-Solomon codes and the high rate LDPC code specified in sections 4 and 6 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 ~~7~~5 or the LDPC codes specified in section 6 may be used to obtain even greater coding gain where the environment permits.

NOTE – In this ~~Recommendation~~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.

2.2.3 FRAME VALIDATION

~~Some codes are also used to check~~After decoding is performed, the upper layers at the receiving end also need to know whether or not each decoded Transfer Frame can be used as a valid data unit~~ by the upper layers at the receiving end~~; i.e., an indication of the quality of the received frame is needed. This function is called Frame Validation. The Reed-Solomon (*E*=16) and LDPC decoders can determine, with a very high probability, whether or not ~~it~~they can correctly decode a Transfer Frame. Therefore, the Reed-Solomon ~~code is~~and LDPC codes are also used for Frame Validation. When the Reed-Solomon ~~code is~~(*E*=16) or LDPC codes are not used, the Frame Error Control Field defined in references [1] or [2] ~~shall be~~is used for Frame Validation.

~~NOTE – Frame Validation explained above presupposes correct frame synchronization. That is, a Transfer Frame declared valid by the Reed-Solomon decoder is valid only if the Transfer Frame is correctly synchronized. If a Transfer Frame is not correctly synchronized, then the Reed-Solomon decoder may perform meaningless error correction against the Transfer Frame and declare it valid.~~

2.2.4 SYNCHRONIZATION

This ~~Recommendation~~Recommended Standard specifies a method for synchronizing Transfer Frames using an Attached Sync Marker (ASM) (see section 7).

The ASM may also be used for resolution of data ambiguity (sense of ‘1’ and ‘0’) if data ambiguity is not resolved by the modulation method used in the Physical Layer.

2.2.5 PSEUDO-RANDOMIZING

~~This Recommendation specifies an optional pseudo-randomizer to improve symbol transition density as an aid to bit synchronization (see section 8).~~

This Recommended Standard specifies a pseudo-randomizer to improve several aspects of the telemetry link that aid receiver acquisition, bit synchronization (see section 8), convolutional code synchronization, and proper Frame Validation (see 2.2.3).

2.3 INTERNAL ORGANIZATION OF SUBLAYER

2.3.1 SENDING END

Figure 2-3 shows the internal organization of the Synchronization and Channel Coding Sublayer of the sending end. This figure identifies functions performed by the sublayer and shows logical relationships among these functions. The figure is not intended to imply any hardware or software configuration in a real system. Depending on the options actually used for a mission, not all of the functions may be present in the sublayer.

At the sending end, the Synchronization and Channel Coding Sublayer accepts Transfer Frames of fixed length from the Data Link Protocol Sublayer (see figure 2-1), performs functions selected for the mission, and delivers a continuous and contiguous stream of channel symbols to the Physical Layer.

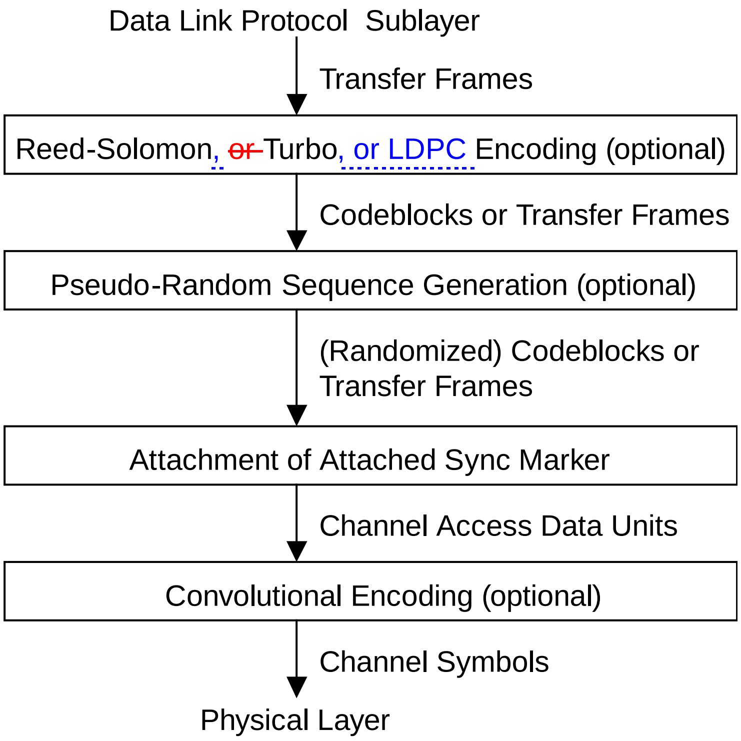

Data Link Protocol Sublayer
Transfer Frames
Reed-Solomon, ~~or~~ Turbo, or LDPC Encoding (optional)
Codeblocks or Transfer Frames
Pseudo-Random Sequence Generation (optional)
(Randomized) Codeblocks or Transfer Frames
Attachment of Attached Sync Marker
Channel Access Data Units
Convolutional Encoding (optional)
Channel Symbols
Physical Layer

Figure 2-3: Internal Organization of the Sublayer at the Sending End

2.3.2 RECEIVING END

Figure 2-4 shows the internal organization of the Synchronization and Channel Coding Sublayer of the receiving end. This figure identifies functions performed by the sublayer and shows logical relationships among these functions. The figure is not intended to imply any hardware or software configuration in a real system. Depending on the options actually used for a mission, not all of the functions may be present in the sublayer.

At the receiving end, the Synchronization and Channel Coding Sublayer accepts a continuous and contiguous stream of channel symbols from the Physical Layer, performs functions selected for the mission, and delivers Transfer Frames to the Data Link Protocol Sublayer.

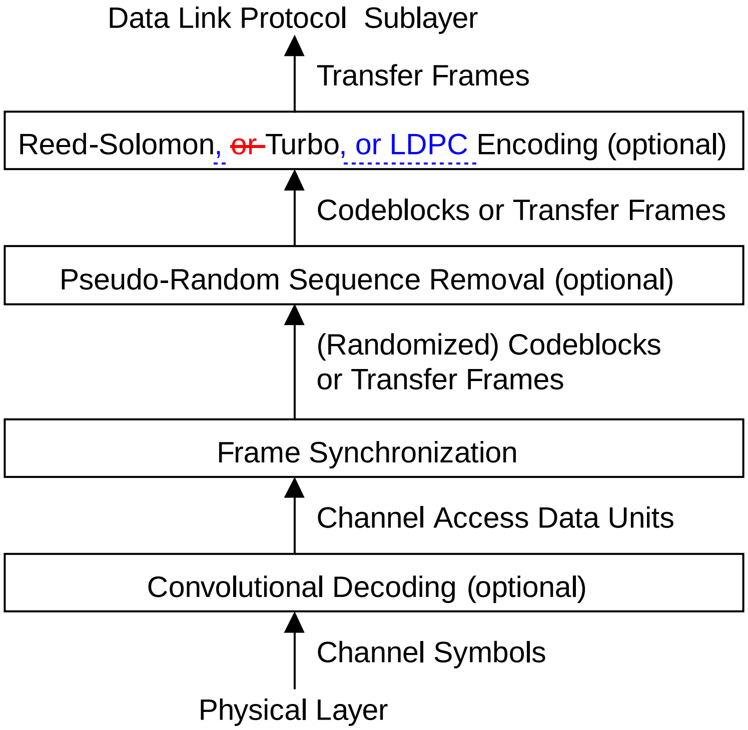

Data Link Protocol Sublayer
Transfer Frames
Reed-Solomon, ~~or~~ Turbo, or LDPC Encoding (optional)
Codeblocks or Transfer Frames
Pseudo-Random Sequence Removal (optional)
(Randomized) Codeblocks or Transfer Frames
Frame Synchronization
Channel Access Data Units
Convolutional Decoding (optional)
Channel Symbols
Physical Layer

Figure 2-4: Internal Organization of the Sublayer at the Receiving End

3 CONVOLUTIONAL ~~CODING~~CODES

~~3.1 BASIC CONVOLUTIONAL CODE~~

~~3.1.1 BASIC CONVOLUTIONAL CODE DESCRIPTION~~

3.1 INTRODUCTION

~~**3.1.1.1**~~ The basic convolutional code is a rate (*r*) 1/2, constraint-length (*k*) 7 transparent code which is well suited for channels with predominantly Gaussian noise. This code is defined in 3.2. When this code is punctured according to 3.3, higher code rates ~~(lower overhead)~~ may be achieved~~,~~ although with somewhat lower error correcting performance.

~~**3.1.1.2** The convolutional decoder is a maximum-likelihood (Viterbi) decoder.~~

~~NOTES~~

~~1 Basic convolutional code, by itself, cannot guarantee sufficient symbol transitions when multiplexing schemes are used, e.g., those implemented in Quadrature Phase Shift Keying (QPSK). Therefore, the Pseudo-Randomizer defined in section 8 is required unless the system designer verifies that sufficient symbol transition density is assured by other means when the Randomizer is not used.~~

~~2 If the decoder's correction capability is exceeded, undetected burst errors may appear in the output. For this reason, when TM or AOS Transfer Frames are used, the Frame Error Control Field (FECF) specified in references [1] and [2] is required to validate the Transfer Frame unless the Reed-Solomon code is used (see section 4).~~

~~**3.1.1.3** It is recommended that soft bit decisions with at least 3-bit quantization be used whenever constraints (such as location of decoder) permit.~~
Quantization. It is suggested that soft bit decisions with at least three-bit quantization be used whenever constraints (such as complexity of decoder) permit.

Phase ambiguity. Differential encoding can be used for phase ambiguity resolution. Since the convolutional codes are transparent, differential encoding can be used before the convolutional encoder. Differential encoding after the convolutional encoder is not advised because it introduces considerable loss of performance. It also would require differential detection, which is more complex with soft symbols.

Data Randomization. An inverter is specified with the basic convolutional code to assure sufficient bit transitions to keep receiver symbol synchronizers in lock, when used with Binary Phase Shift Keying (BPSK) modulation. Sufficient bit transitions cannot be guaranteed if some multiplexing schemes are used, e.g., with Quadrature Phase Shift Keying (QPSK) modulation, or if a punctured convolutional code is used. There are also data patterns for which convolutional code synchronization cannot be determined. To address these issues, to aid signal acquisition, and to mitigate unusual spectral characteristics in the transmitted signal, the pseudo-randomizer defined in section 8 is required unless the system designer verifies that these concerns are resolved by other means.

Frame validation. If the decoder's correction capability is exceeded, undetected burst errors may appear in the output. For this reason, when TM or AOS Transfer Frames are used, the Frame Error Control Field (FECF) specified in references [1] and [2] is required to validate the Transfer Frame, unless the convolutional code is concatenated with an outer Reed-Solomon code (see section 4).

3.2 BASIC CONVOLUTIONAL CODE SPECIFICATION

3.2.1 Th~~is~~e recommended basic convolutional code is a non-systematic code and a specific decoding procedure, with the following characteristics:

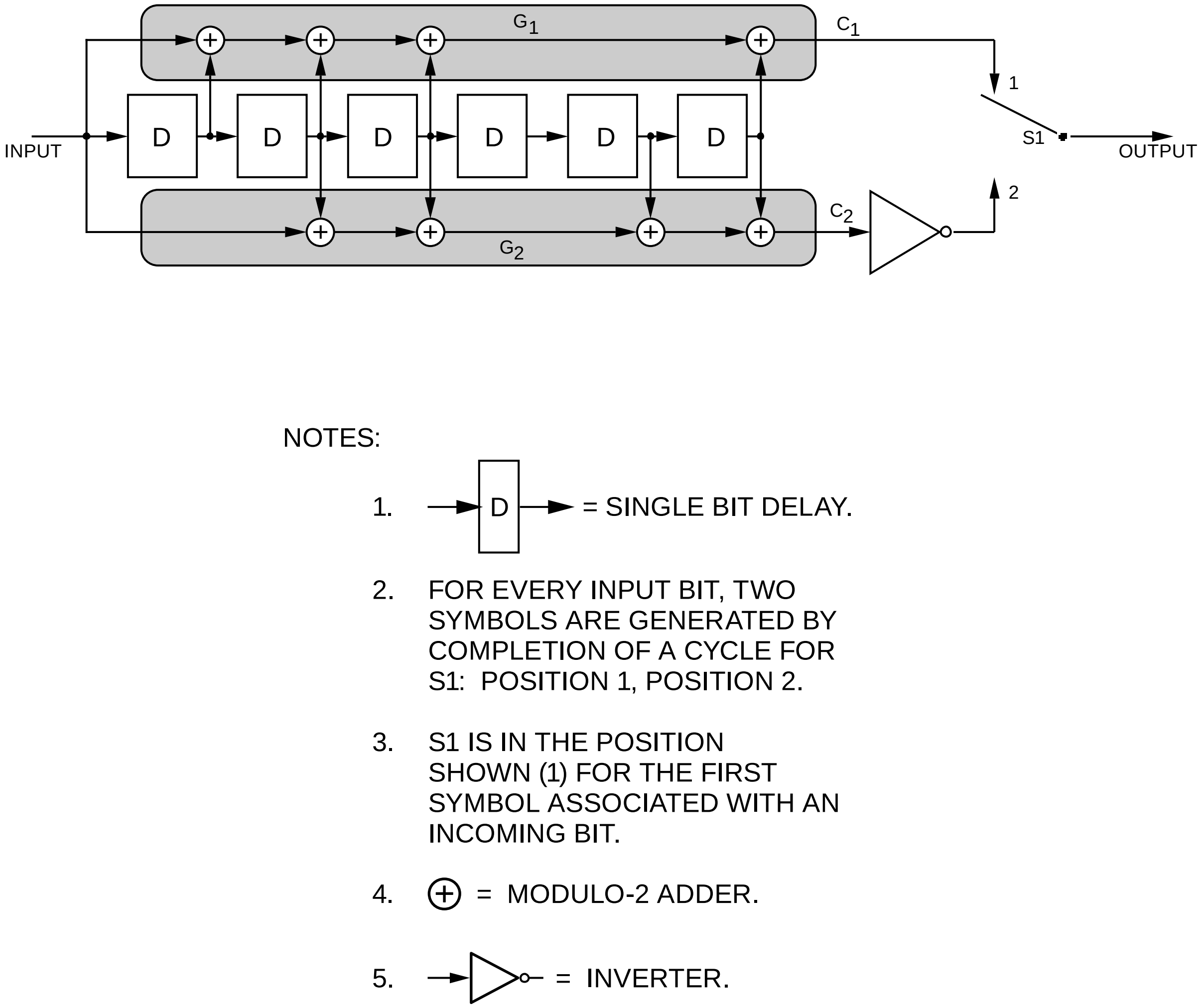
(1) Nomenclature:	Convolutional code with maximum-likelihood (Viterbi) decoding.
(2) Code rate (*r*):	1/2 bit per symbol.
(3) Constraint length (~~*K*~~*k*):	7 bits.
(4) Connection vectors:	G1 = 1111001 (171 octal); G2= 1011011(133 octal).
(5) Symbol inversion:	On output path of G2.

NOTE – An encoder block diagram is shown in figure 3-1. G2 inversion provides no benefit when even-order modulations higher than BPSK are used where encoding is not done independently on each channel.

3.2.2 The output symbol sequence is: $C_1(1), \overline{C_2(1)}, C_1(2), \overline{C_2(2)}$. . . .

3.2.3 When suppressed-carrier modulation systems are used, Non-Return-to-Zero-Mark (NRZ-M) or Non-Return-to-Zero-Level (NRZ-L) may be used as a modulating waveform. If the user contemplates conversion of his modulating waveform from NRZ-L to NRZ-M, such conversion should be performed on-board at the input to the convolutional encoder. Correspondingly, the conversion on the ground from NRZ-M to NRZ-L should be performed at the output of the convolutional decoder. This avoids unnecessary link performance loss.

3.2.4 When a fixed pattern (the fixed part of the convolutionally encoded Attached Sync Marker) in the symbol stream is used to provide node synchronization for the Viterbi decoder, care must be taken to account for any modification of the pattern resulting from the modulating waveform conversion.



NOTES:

1. D = SINGLE BIT DELAY.

2. FOR EVERY INPUT BIT, TWO SYMBOLS ARE GENERATED BY COMPLETION OF A CYCLE FOR S1: POSITION 1, POSITION 2.

3. S1 IS IN THE POSITION SHOWN (1) FOR THE FIRST SYMBOL ASSOCIATED WITH AN INCOMING BIT.

4. ⊕ = MODULO-2 ADDER.

5. ▷○ = INVERTER.

Figure 3-1: Basic Convolutional Encoder Block Diagram

3.3 PUNCTURED CONVOLUTIONAL CODES

~~3.2.1 GENERAL~~

~~The code rate (*r*=1/2), constraint length (*k*=7) convolutional code can be modified to achieve an increase in bandwidth efficiency. This modification is achieved by using a puncture pattern P(*r*). Puncturing removes some of the symbols before transmission, providing lower overhead and lower bandwidth expansion than the original code, but with slightly reduced error correcting performance.~~

3.3.1 PUNCTURED CONVOLUTIONAL CODES DESCRIPTION

Puncturing allows a single code rate of either 2/3, 3/4, 5/6 or 7/8 to be selected. The four different puncturing schemes allow selection of the most appropriate level of error correction and symbol rate for a given service or data rate. Figure 3-2 depicts the punctured encoding scheme.

~~NOTE The symbol inverter associated with G2 in the rate 1/2 code (defined in 3.1.2) is omitted here. Therefore, the Pseudo-Randomizer defined in section 7 is required unless the system designer verifies that sufficient symbol transition density is assured by other means when the Randomizer is not used.~~

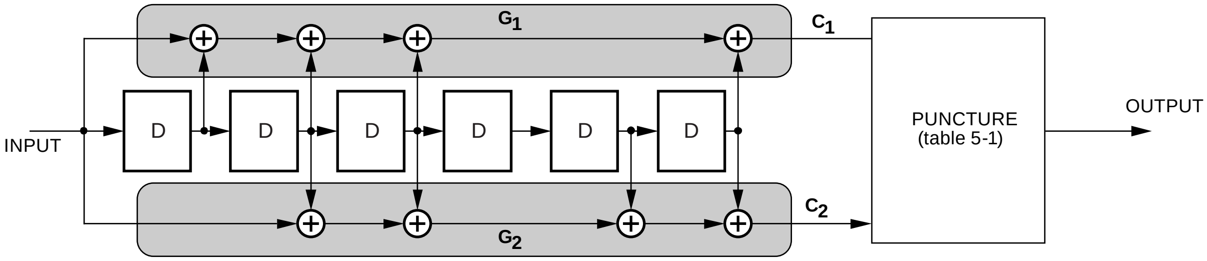


Figure 3-2: Punctured Encoder Block Diagram

3.3.2 PUNCTURED CONVOLUTIONAL CODES SPECIFICATION

3.3.2.1 The punctured convolutional code has the following characteristics:

(1) Nomenclature:	Punctured convolutional code with maximum-likelihood (Viterbi) decoding.
(2) Code rate (*r*):	1/2, punctured to 2/3, 3/4, 5/6 or 7/8.
(3) Constraint length (~~*K*~~*k*):	7 bits.
(4) Connection vectors:	G1 = 1111001 (171 octal); G2 = 1011011 (133 octal).
(5) Symbol inversion:	None.

3.3.2.2 The puncturing patterns for each of the punctured convolutional code rates are defined by table 3-1.

Table 3-1: Puncture Code Patterns for Convolutional Code Rates

Puncturing Pattern 1 = transmitted symbol 0 = non-transmitted symbol	**Code Rate**	**Output Sequence** $C_1(t)$, $C_2(t)$ denote values at bit time t
C_1: 1 0 C_2: 1 1	2/3	$C_1(1)$ $C_2(1)$ $C_2(2)$ ...
C_1: 1 0 1 C_2: 1 1 0	3/4	$C_1(1)$ $C_2(1)$ $C_2(2)$ $C_1(3)$ ...
C_1: 1 0 1 0 1 C_2: 1 1 0 1 0	5/6	$C_1(1)$ $C_2(1)$ $C_2(2)$ $C_1(3)$ $C_2(4)$ $C_1(5)$ ...
C_1: 1 0 0 0 1 0 1 C_2: 1 1 1 1 0 1 0	7/8	$C_1(1)$ $C_2(1)$ $C_2(2)$ $C_2(3)$ $C_2(4)$ $C_1(5)$ $C_2(6)$ $C_1(7)$ ...

4 REED-SOLOMON ~~CODING~~CODES

4.1 INTRODUCTION

~~4.1.1~~ The Reed-Solomon (R-S) codes defined in this section ~~is a~~are powerful burst error correcting codes. ~~In addition, the code chosen has an extremely low undetected error rate. This means that the decoder can reliably indicate whether or not it can make the proper corrections. To achieve this reliability, proper codeblock synchronization is mandatory.~~

~~4.1.2~~ One of two different error-correcting options may be chosen. For maximum performance (at the expense of accompanying overhead) the *E*=16 option can correct 16 R-S symbols in error per codeword. For lower overhead (with reduced performance) the *E*=8 option can correct 8 R-S symbols per codeword.~~ The two options shall not be mixed in a single Physical Channel.~~

~~NOTES~~

~~1~~ ~~The extremely low undetected error rate of this code means that the R-S decoder can, with a high degree of certainty, validate the decoded codeblock and consequently the contained TM Transfer Frame (reference [1]) or AOS Transfer Frame (reference [2]). For this reason, the Frame Error Control Field (FECF) specified in references [1] and [2] is not required when this Reed-Solomon Code is used (see section 1).~~

~~2~~ ~~The Reed-Solomon coding, by itself, cannot guarantee sufficient channel symbol transitions to keep receiver symbol synchronizers in lock. Therefore, the Pseudo-Randomizer defined in section 7 is required unless the system designer verifies that sufficient symbol transition density is assured by other means when the Randomizer is not used.~~

~~4.1.3~~ The Reed-Solomon code may be used alone, and as such it provides an excellent forward error correction capability in a burst-noise channel. However, should the Reed-Solomon code alone not provide sufficient coding gain, it may be concatenated with the convolutional code defined in section 3. Used this way, the Reed-Solomon code is the *outer code*, while the convolutional code is the *inner code*.

Data Randomization. The recommended Reed-Solomon codes, by themselves, cannot guarantee sufficient bit transitions to keep receiver symbol synchronizers in lock. Because of the quasi-cyclic nature of these codes, undetected decoding errors may result from incorrect codeblock synchronization. To address these issues, to aid signal acquisition, and to mitigate unusual spectral characteristics in the transmitted signal, the pseudo-randomizer defined in section 8 is required unless the system designer verifies that these concerns are resolved by other means.

Frame validation. 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]) or AOS Transfer Frame (reference [2]).

For this reason, the Frame Error Control Field (FECF) specified in references [1] and [2] is optional, and the system designer may choose to use it for additional codeblock validation, particularly with the *E*=8 code.

4.2 SPECIFICATION

The parameters of the selected Reed-Solomon (R-S) code are as follows:

a) $J = 8$ bits per R-S symbol.

b) E = Reed-Solomon error correction capability, in symbols, within a R-S codeword. E may be selected to be 16 or 8 R-S symbols.

c) General characteristics of Reed-Solomon codes:

   1) J, E, and I (the depth of interleaving) are independent parameters.

   2) $n = 2^J – 1 = 255$ symbols per R-S codeword.

   3) $2E$ is the number of R-S symbols among n symbols of an R-S codeword representing parity checks.

   4) $k = n – 2E$ is the number of R-S symbols among n R-S symbols of an R-S codeword representing information.

d) Field generator polynomial:

$$\mathrm{F}(x) = x^8 + x^7 + x^2 + x + 1$$

   over GF(2).

e) Code generator polynomial:

$$\mathrm{g}(x) = \prod_{j=128-E}^{127+E} (x - \alpha^{11j}) \qquad = \sum_{i=0}^{2E} G_i x^i$$

   over GF(2^8), where F(α) = 0.

   It should be recognized that α^{11} is a primitive element in GF(2^8) and that F(x) and g(x) characterize a (255,223) Reed-Solomon code when $E = 16$ and a (255,239) Reed-Solomon code when $E = 8$.

f) The selected code is a systematic code. This results in a systematic codeblock.

g) Symbol interleaving:

   The allowable values of interleaving depth are I=1, 2, 3, 4, 5, and 8. I=1 is equivalent to the absence of interleaving. The interleaving depth shall normally be fixed on a Physical Channel for a Mission Phase. Symbol interleaving is accomplished in a manner functionally described with the aid of figure 4-1. (It should be noted that this functional description does not necessarily correspond to the physical implementation of an encoder.)

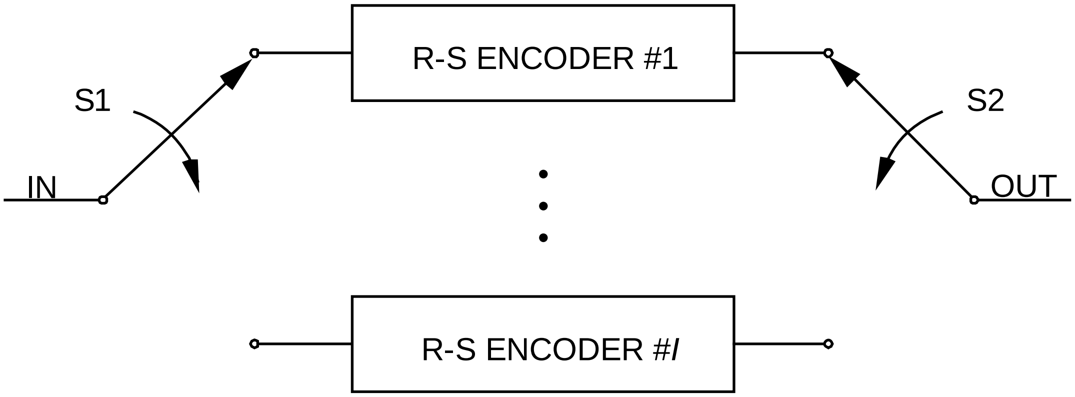


Figure 4-1: Functional Representation of R-S Interleaving

Data bits to be encoded into a single Reed-Solomon Codeblock enter at the port labeled ‘IN’. Switches S1 and S2 are synchronized together and advance from encoder to encoder in the sequence 1,2, . . ., *I*, 1,2, . . ., *I*, . . ., spending one R-S symbol time (8 bits) in each position.

One codeblock will be formed from *kI* R-S symbols entering ‘IN’. In this functional representation, a space of 2*EI* R-S symbols in duration is required between each entering set of *kI* R-S information symbols.

Because of the action of S1, each encoder accepts *k* of these symbols, with each symbol spaced *I* symbols apart (in the original stream). These *k* symbols are passed directly to the output of each encoder. The synchronized action of S2 reassembles the symbols at the port labeled ‘OUT’ in the same way as they entered at ‘IN’.

Following this, each encoder outputs its 2*E* check symbols, one symbol at a time, as it is sampled in sequence by S2.

If, for *I*=5, the original symbol stream is

$$d_1^1 \ldots d_1^5 \, d_2^1 \ldots d_2^5 \ldots d_k^1 \ldots d_k^5 \quad [2E \times 5 \text{ spaces}]$$

then the output is the same sequence with the [2*E* × 5 spaces] filled by the [2*E*× 5] check symbols as shown below:

$$p_1^1 \ldots p_1^5 \ldots p_{2E}^1 \ldots p_{2E}^5$$

where

$$d_1^i \, d_2^i \ldots d_k^i \; p_1^i \ldots p_{2E}^i$$

is the R-S codeword produced by the ith encoder. If q virtual fill symbols are used in each codeword, then replace k by $(k - q)$ in the above discussion.

With this method of interleaving, the original kI consecutive information symbols that entered the encoder appear unchanged at the output of the encoder with $2EI$ R-S check symbols appended.

h) Maximum codeblock length:

The maximum codeblock length, in R-S symbols, is given by:

$$L_{\max} = nI = (2^J - 1)I = 255I$$

i) Shortened codeblock length:

A shortened codeblock length may be used to accommodate frame lengths smaller than the maximum. However, since the Reed-Solomon code is a block code, the decoder must always operate on a full block basis. To achieve a full codeblock, ‘virtual fill’ must be added to make up the difference between the shortened block and the maximum codeblock length. The characteristics and limitations of virtual fill are covered in ~~subsection 6.2(j)~~4.2j). Since the virtual fill is not transmitted, both encoder and decoder must be set to insert it with the proper length for the encoding and decoding processes to be carried out properly.

When an encoder (initially cleared at the start of a block) receives $kI–Q$ symbols representing information (where Q, representing fill, is a multiple of I, and is less than kI), $2EI$ check symbols are computed over kI symbols, of which the leading Q symbols are treated as all-zero symbols. A $(nI–Q, kI–Q)$ shortened codeblock results where the leading Q symbols (all zeros) are neither entered into the encoder nor transmitted.

NOTE – It should be noted that shortening the transmitted codeblock length in this way changes the overall performance to a degree dependent on the amount of virtual fill used. Since it incorporates no virtual fill, the maximum codeblock length allows full performance. In addition, as virtual fill in a codeblock is increased (at a specific bit rate), the number of codeblocks per unit time that the decoder must handle increases. Therefore, care should be taken so that the maximum operating speed of the decoder (codeblocks per unit time) is not exceeded.

j) Reed-Solomon codeblock partitioning and virtual fill:

The R-S codeblock is partitioned as shown in figure 4-2.

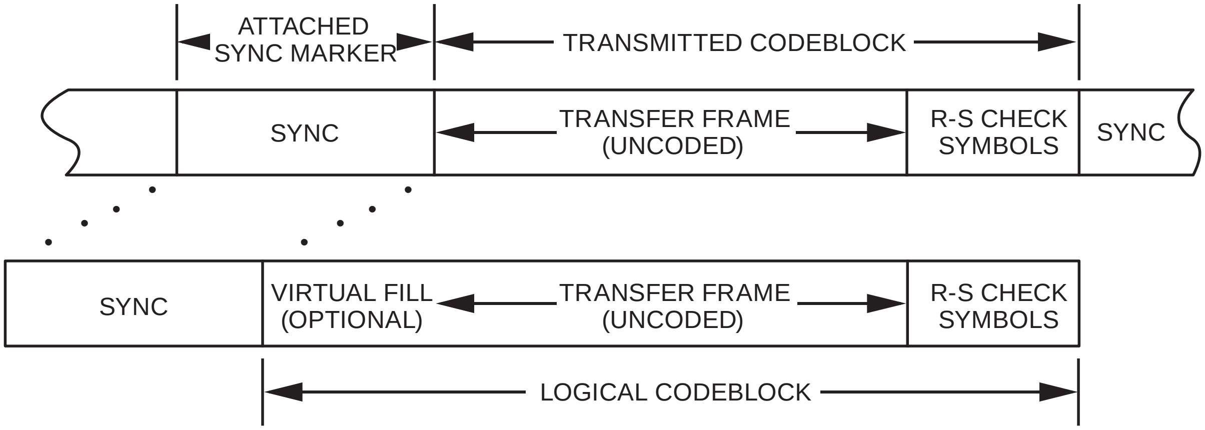


Figure 4-2: Reed-Solomon Codeblock Partitioning

The **Reed-Solomon Check Symbols** consist of the trailing 2*EI* symbols (2*EIJ* bits) of the codeblock. (As an example, when *E* = 16 and *k* = 223, for *I*=5 this is always 1280 bits.)

The **Transfer Frame** is defined by the TM Space Data Link Protocol (reference [1]) or the AOS Space Data Link Protocol (reference [2]). For constraints on the length of the Transfer Frame, see section 9.

The **Attached Sync Marker** used with R-S coding is a 32-bit pattern specified in section 7 as an aid to synchronization. It precedes the Transmitted Codeblock. Frame synchronizers should, therefore, be set to expect a marker at every Transmitted Codeblock + 32 bits.

The **Transmitted Codeblock** consists of the Transfer Frame (without the 32-bit sync marker) and R-S check symbols. It is the received data entity physically fed into the R-S decoder. (As an example, when *E* = 16 and *k* = 223, using *I*=5 and no virtual fill, the length of the transmitted codeblock will be 10,200 bits; if virtual fill is used, it will be incrementally shorter, depending on the amount used.)

The **Logical Codeblock** is the logical data entity operated upon by the R-S decoder. It can have a different length than the transmitted codeblock because it accounts for the amount of virtual fill that was introduced. (As an example, when *E* = 16 and *k* = 223, for *I*=5 the logical codeblock always appears to have exactly 10,200 bits in length.)

Virtual fill is used to logically complete the codeblock and is not transmitted. If used, virtual fill shall:

1) consist of all zeros;

2) not be transmitted;

3) not change in length for a Mission Phase on a particular Physical Channel;

4) be inserted only at the beginning of the codeblock (i.e., after the attached sync marker but before the beginning of the transmitted codeblock);

5) be inserted only in integer multiples of $8I$ bits.

k) Dual basis symbol representation and ordering for transmission:

Each 8-bit Reed-Solomon symbol is an element of the finite field GF(256). Since GF(256) is a vector space of dimension 8 over the binary field GF(2), the actual 8-bit representation of a symbol is a function of the particular basis that is chosen.

One basis for GF(256) over GF(2) is the set ($1, \alpha^1, \alpha^2, \ldots, \alpha^7$). This means that any element of GF(256) has a representation of the form

$$u_7\alpha^7 + u_6\alpha^6 + \ldots + u_1\alpha^1 + u_0\alpha^0$$

where each u_i is either a zero or a one.

Another basis over GF(2) is the set ($1, \beta^1, \beta^2, \ldots, \beta^7$) where $\beta = \alpha^{117}$. To this basis there exists a so-called 'dual basis' ($\ell_0, \ell_1, \ldots, \ell_7$). It has the property that

$$\mathrm{Tr}(\ell_i\beta^j) = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

for each $j = 0, 1, \ldots, 7$. The function Tr(z), called the 'trace', is defined by

$$\mathrm{Tr}(z) = \sum_{k=0}^{7} z^{2^k}$$

for each element z of GF(256). Each Reed-Solomon symbol can also be represented as

$$z_0\ell_0 + z_1\ell_1 + \ldots + z_7\ell_7$$

where each z_i is either a zero or a one.

The representation used in this ~~Recommendation~~Recommended Standard is the dual basis eight-bit string $z_0, z_1, \ldots, z_7$, transmitted in that order (i.e., with z_0 first). The relationship between the two representations is given by the two equations

$$[z_0, \ldots, z_7] = [u_7, \ldots, u_0]\begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \end{bmatrix}$$

and

$$[u_7, \ldots, u_0] = [z_0, \ldots, z_7] \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix}$$

Further information relating the dual basis (Berlekamp) and conventional representations is given in annex E. Also included is a recommended scheme for permitting the symbols generated in a conventional encoder to be transformed to meet the symbol representation required by this document.

l) Synchronization:

Codeblock synchronization of the Reed-Solomon decoder is achieved by synchronization of the Attached Sync Marker associated with each codeblock. (See section 7.)

m) Ambiguity resolution:

The ambiguity between true and complemented data must be resolved so that only true data is provided to the Reed-Solomon decoder. Data in NRZ-L form is normally resolved using the 32-bit Attached Sync Marker, while NRZ-M data is self-resolving.

5 TURBO ~~CODING~~CODES

5.1 INTRODUCTION

~~5.1.1~~ Turbo codes are binary block codes with large code blocks (hundreds or thousands of bits). ~~They are systematic and inherently non-transparent. Phase ambiguities are resolved using Attached Sync Markers (ASMs), which are required for Codeblock synchronization.~~

~~5.1.2~~ Turbo codes may be used to obtain even greater coding gains than those provided by concatenated coding systems. They are systematic and inherently non-transparent.

Licensing issues. Implementers should be aware that a wide class of turbo codes is covered by a patent by France Télécom and Télédiffusion de France under US Patent 5,446,747 and its counterparts in other countries.

~~NOTES~~

~~1 Turbo coding, by itself, cannot guarantee sufficient bit transitions to keep receiver symbol synchronizers in lock. Therefore, the Pseudo-Randomizer defined in section 8 is required unless the system designer verifies that sufficient symbol transition density is assured by other means when the Randomizer is not used.~~

~~2 While providing outstanding coding gain, turbo codes may still leave some residual errors in the decoded output. For this reason, when TM or AOS Transfer Frames are used, the Frame Error Control Field (FECF) specified in references [1] or [2], respectively, is required to validate the Transfer Frame unless the Reed-Solomon code is used. (See section 1.)~~

~~3 Differential encoding (i.e., NRZ-M signaling) after the turbo encoder is not recommended since soft decoding would require the use of differential detection with considerable loss of performance. Differential encoding before the turbo encoder cannot be used because the turbo codes recommended in this document are non-transparent. This implies that phase ambiguities have to be detected and resolved by the frame synchronizer.~~

~~4~~ ~~Implementers should be aware that a wide class of turbo codes is covered by a patent by France Télécom and Télédiffusion de France under US Patent 5,446,747 and its counterparts in other countries.~~ Potential user agencies should direct their requests for licenses to:

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E-mail: christian.hamon@cnet.francetelecom.fr

Phase ambiguity. Differential encoding after the turbo encoder is not advised because it introduces considerable loss of performance. It also would require differential detection, which is more complex with soft symbols. Differential encoding before the turbo encoder cannot be used because the turbo codes recommended in this document are non-transparent. This implies that phase ambiguities have to be detected and resolved by the frame synchronizer. Phase ambiguities are resolved using Attached Sync Markers (ASMs), defined in section 7, which are required for codeblock synchronization.

Data Randomization. The recommended turbo codes, by themselves, cannot guarantee sufficient bit transitions to keep receiver symbol synchronizers in lock. To address this issue, to aid signal acquisition, and to mitigate unusual spectral characteristics in the transmitted signal, the pseudo-randomizer defined in section 8 is required unless the system designer verifies that these concerns are resolved by other means.

Frame validation. While providing outstanding coding gain, turbo codes may still leave some undetected errors in the decoded output. For this reason, when turbo codes are used with TM or AOS Transfer Frames, the Frame Error Control Field (FECF) specified in references [1] or [2], respectively, is required to validate the Transfer Frame.

5.2 SPECIFICATION

5.2.1 A turbo encoder is a combination of two simple encoders. The input is a frame of *k* information bits. The two component encoders generate parity symbols from two simple recursive convolutional codes, each with a small number of states. The information bits are also sent uncoded. A key feature of turbo codes is an interleaver, which permutes bit-wise the original *k* information bits before input to the second encoder.

5.2.2 The recommended turbo code is a systematic code with the following specifications:

a)	Code type:	Systematic parallel concatenated turbo code.
b)	Number of component codes:	2 (plus an uncoded component to make the code systematic).
c)	Type of component codes:	Recursive convolutional codes.
d)	Number of states of each convolutional component code:	16.
e)	Nominal code rates:	*r* = 1/2, 1/3, 1/4, or 1/6 (selectable).

NOTE – Because of ‘trellis termination’ symbols (see ~~subsection 5.2(j)~~5.2.2j)), the true code rates (defined as the ratios of the information block lengths to the codeblock lengths in table 5-2) are slightly smaller than the nominal code rates. In this ~~Recommendation~~Recommended Standard, the term ‘code rate’ always refers to the nominal code rates, *r* = 1/2, 1/3, 1/4, or 1/6.

f) The specified information block lengths *k* are shown in table 5-1. They are chosen for compatibility with the corresponding Reed-Solomon interleaving depths, also shown in table ~~7-1~~5-1.

The corresponding codeblock lengths in bits, *n*=(*k*+4)/*r*, for the specified code rates are shown in table 5-2.

Table 5-1: Specified Information Block Lengths

Information block length *k*, bits	Corresponding Reed-Solomon interleaving depth *I*	Notes
1784 (=223 × 1 octets)	1	For very low data rates or low latency
3568 (=223 × 2 octets)	2	
7136 (=223 × 4 octets)	4	
8920 (=223 × 5 octets)	5	
16384	Not Applicable	For highest coding gain

Table 5-2: Codeblock Lengths for Supported Code Rates (Measured in Bits)

Information block length *k*	Codeblock length *n*			
	rate 1/2	rate 1/3	rate 1/4	rate 1/6
1784	3576	5364	7152	10728
3568	7144	10716	14288	21432
7136	14280	21420	28560	42840
8920	17848	26772	35696	53544
16384	32776	49164	65552	98328

g) Turbo code permutation:

The interleaver is a fundamental component of the turbo encoding and decoding process. The interleaver for turbo codes is a fixed bit-by-bit permutation of the entire block of data. Unlike the symbol-by-symbol rectangular interleaver used with Reed-Solomon codes, the turbo code permutation scrambles individual bits and resembles a randomly selected permutation in its lack of apparent orderliness.

The recommended permutation for each specified block length k is given by a particular reordering of the integers 1, 2, . . ., k as generated by the following algorithm.

First express k as $k=k_1k_2$. The parameters k_1 and k_2 for the specified block sizes are given in table 5-3.

Next do the following operations for s=1 to s=k to obtain permutation numbers $\pi(s)$. In the equation below, $\lfloor x \rfloor$ denotes the largest integer less than or equal to x, and p_q denotes one of the following eight prime integers:

$$p_1 = 31; p_2 = 37; p_3 = 43; p_4 = 47; p_5 = 53; p_6 = 59; p_7 = 61; p_8 = 67$$

Table 5-3: Parameters k_1 and k_2 for Specified Information Block Lengths

Information block length	k_1	k_2
1784	8	223
3568	8	223 × 2
7136	8	223 × 4
8920	8	223 × 5
16384	(NOTE)	(NOTE)
NOTE – These parameters are currently under study and will be incorporated in a later revision.		

$$m = (s-1) \bmod 2$$

$$i = \left\lfloor \frac{s-1}{2\,k_2} \right\rfloor$$

$$j = \left\lfloor \frac{s-1}{2} \right\rfloor - i\,k_2$$

$$t = (19i+1) \bmod \frac{k_1}{2}$$

$$q = t \bmod 8 + 1$$

$$c = (p_q\,j + 21m) \bmod k_2$$

$$\pi(s) = 2(t + c\frac{k_1}{2} + 1) - m$$

The interpretation of the permutation numbers is such that the sth bit read out on line ‘in b’ in figure 5-2 is the $\pi(s)$th bit of the input information block, as shown in figure 5-1.

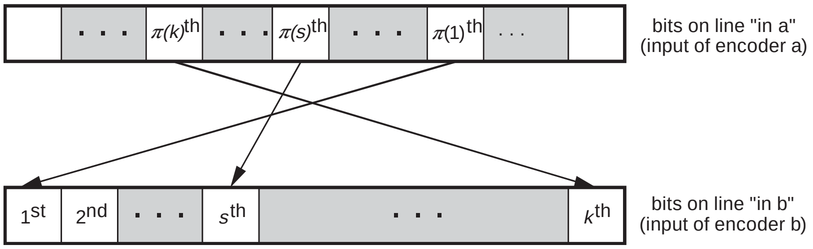

Figure 5-1: Interpretation of Permutation

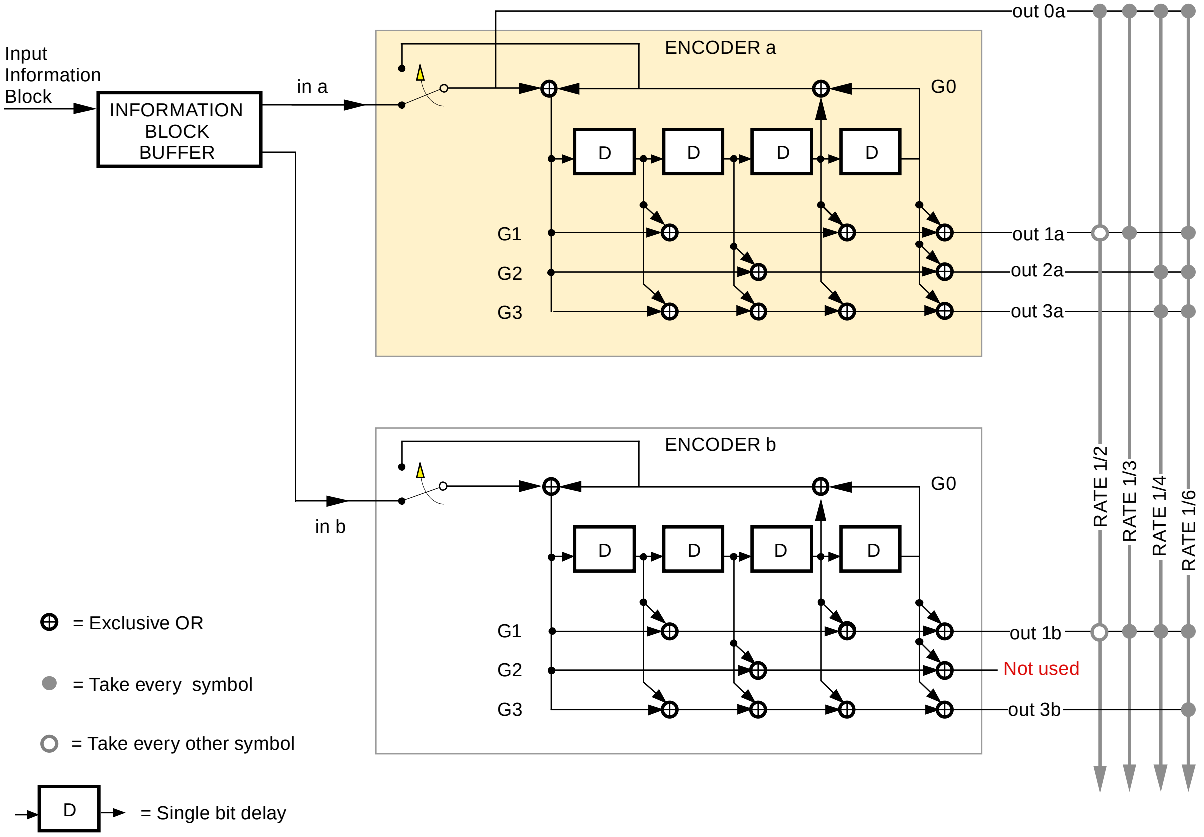

Figure 5-2: Turbo Encoder Block Diagram

h) Backward and forward connection vectors (see figure 5-2):

1) Backward connection vector for both component codes and all code rates: G0 = 10011.

2) Forward connection vector for both component codes and rates 1/2 and 1/3: G1 = 11011. Puncturing of every other symbol from each component code is necessary for rate 1/2. No puncturing is done for rate 1/3.

3) Forward connection vectors for rate 1/4: G2 = 10101, G3 = 11111 (1st component code); G1 = 11011 (2nd component code). No puncturing is done for rate 1/4.

4) Forward connection vectors for rate 1/6: G1 = 11011, G2 = 10101, G3 = 11111 (1st component code); G1 = 11011, G3 = 11111 (2nd component code). No puncturing is done for rate 1/6.

i) Turbo encoder block diagram:

The recommended encoder block diagram is shown in figure ~~7-2~~5-2. Each input frame of *k* information bits is held in a frame buffer, and the bits in the buffer are read out in two different orders for the two component encoders. The first component encoder (a) operates on the bits in unpermuted order ('in a'), while the second component encoder (b) receives the same bits permuted by the interleaver ('in b'). The read-out addressing for 'in a' is a simple counter, while the addressing for 'in b' is specified by the turbo code permutation described in ~~subsection 7.2(g)~~5.2.2g).

The component encoders are recursive convolutional encoders realized by feedback shift registers as shown in figure ~~7-2~~5-2. The circuits shown in this figure implement the backward connection vector, G0, and the forward connection vectors, G1, G2, G3, specified in ~~subsection 7.2(h)~~5.2.2h). A key difference between these convolutional component encoders and the standalone convolutional encoder recommended in section 3 is their recursiveness. In the figure this is indicated by the signal (corresponding to the backward connection vector G0) fed back into the leftmost adder of each component encoder.

j) Turbo Codeblock specification:

Both component encoders in figure 5-2 are initialized with '0's in all registers, and both are run for a total of *k*+4 bit times, producing an output Codeblock of (*k*+4)/*r* encoded symbols, where *r* is the nominal code rate. For the first *k* bit times, the input switches are in the lower position (as indicated in the figure) to receive input data. For the final 4 bit times, these switches move to the upper position to receive feedback from the shift registers. This feedback cancels the same feedback sent (unswitched) to the leftmost adder and causes all four registers to become filled with zeros after the final 4 bit times. Filling the registers with zeros is called terminating the trellis. During trellis termination the encoder continues to output nonzero encoded symbols. In particular, the 'systematic uncoded' output (line 'out 0a' in the figure) includes an extra 4 bits from the feedback line in addition to the *k* information bits.

In figure 5-2, the encoded symbols are multiplexed from top-to-bottom along the output line for the selected code rate to form the Turbo Codeblock. For the rate 1/3 code, the output sequence is (out 0a, out 1a, out 1b); for rate 1/4, the sequence is (out 0a, out 2a, out 3a, out 1b); for rate 1/6, the sequence is (out 0a, out 1a, out 2a, out 3a, out 1b, out 3b). These sequences are repeated for (*k*+4) bit times. For the rate 1/2 code, the output sequence is (out 0a, out 1a, out 0a, out 1b), repeated (*k*+4)/2 times. ~~Note that t~~This pattern implies that out 1b is the first to be punctured, out 1a is the second, and so forth. The Turbo Codeblocks constructed from these output sequences are depicted in figure 5-3 for the four nominal code rates.

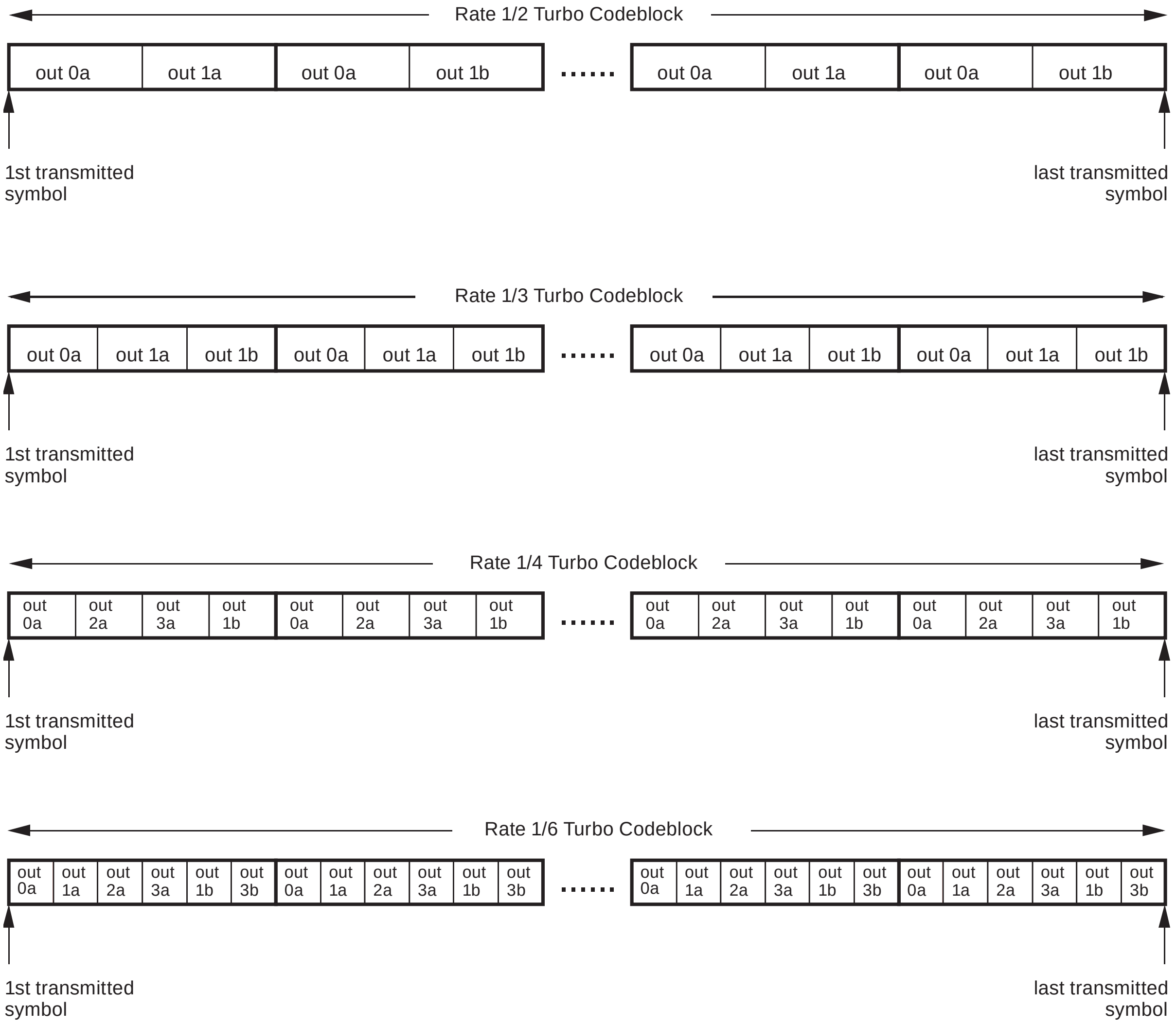

Figure 5-3: Turbo Codeblocks for Different Code Rates

k) Turbo Codeblock synchronization:

Codeblock synchronization of the turbo decoder is achieved by synchronization of an Attached Sync Marker (ASM) associated with each Turbo Codeblock. The ASM is a bit pattern specified in section 7 as an aid to synchronization, and it precedes the Turbo Codeblock. Frame synchronizers should be set to expect a marker at a recurrence interval equal to the length of the ASM plus that of the Turbo Codeblock.

A diagram of a Turbo Codeblock with ASM is shown in figure 5-4. ~~Note that t~~The length of the Turbo Codeblock is inversely proportional to the nominal code rate *r*.

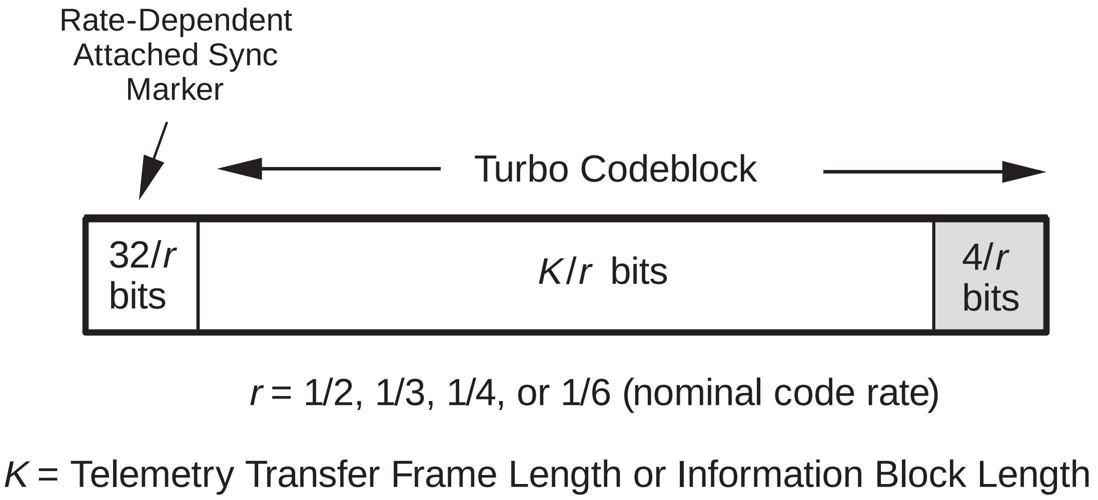
Rate-Dependent Attached Sync Marker
Turbo Codeblock
32/*r* bits
K/*r* bits
4/*r* bits
r = 1/2, 1/3, 1/4, or 1/6 (nominal code rate)
K = Telemetry Transfer Frame Length or Information Block Length

Figure 5-4: Turbo Codeblock with Attached Sync Marker

6 LOW DENSITY PARITY CHECK CODES

6.1 INTRODUCTION

Low-Density Parity-Check (LDPC) codes are binary block codes with large code blocks (hundreds or thousands of bits). They may be used to obtain greater coding gains than those provided by concatenated coding systems.

An LDPC code is specified indirectly by a *v*-by-*w* parity check matrix H consisting of *v* linearly independent rows. Parity check matrices may include additional linearly dependent rows without changing the code. A coded sequence of *w* bits must lie in the *w*–*v* dimensional dual space of H; that is, it must satisfy all *v* parity check equations corresponding to the *v* rows of H. An encoder maps an input frame of *k* information bits uniquely into a codeblock of *n* bits. LDPC codes may be shortened or expurgated so that $k<w-v$, and the remaining dimensions of the code remain unused. LDPC codes may also be extended or punctured to make *n* greater or less than *w*.

Subsection 6.2 describes a code with a rate of approximately 7/8, and 6.3 describes a set of nine codes with rates 1/2, 2/3, and 4/5. These codes are systematic and non-transparent.

Licensing issues. Implementers should be aware that the codes optimized for deep space applications are covered by US Patent 7,343,539. Potential user agencies should direct their requests for licenses to:

Office of Technology Transfer,
California Institute of Technology,
1200 E. California Blvd., Mail Code 210-85,
Pasadena, CA 91125.

Phase ambiguity. Differential encoding after the LDPC encoder is not advised because it introduces considerable loss of performance. It also would require differential detection, which is more complex with soft symbols. Differential encoding before the LDPC encoder cannot be used because the LDPC codes recommended in this document are non-transparent. This implies that phase ambiguities have to be detected and resolved by the frame synchronizer. Phase ambiguities are resolved using Attached Sync Markers (ASMs) defined in section 7, which are required for codeblock synchronization.

Data Randomization. The recommended LDPC codes, by themselves, cannot guarantee sufficient bit transitions to keep receiver symbol synchronizers in lock. Because of the quasi-cyclic nature of these codes, undetected decoding errors may result from incorrect codeblock synchronization. To address these issues, to aid signal acquisition, and to mitigate unusual spectral characteristics in the transmitted signal, the pseudo-randomizer defined in section 8 is required unless the system designer verifies that these concerns are resolved by other means.

Frame validation. The undetected error rates of these LDPC codes lie several orders of magnitude below detected frame and bit error rates for any given operating signal-to-noise ratio. Therefore the LDPC decoder may be used alone to validate the codeblock, and consequently the contained TM Transfer Frame (reference [1]) or AOS Transfer Frame (reference [2]). The Frame Error Control Field (FECF) specified in references [1] and [2] is optional, and the system designer may choose to use it for additional codeblock validation.

6.2 LOW DENSITY PARITY CHECK CODE OPTIMIZED FOR NEAR-EARTH APPLICATIONS

6.2.1 DESCRIPTION OF THE CODE

The recommended code is an expurgated, shortened, and extended version of a basic LDPC code. The basic (8176,7156) code is transparent, although the modified version of this code is not, because of the sense of the fill bits.

This code is used with the 32-bit ASM shown in figure 7-1.

6.2.2 BASIC (8176,7156) LDPC CODE

For reasons outlined below, the basic (8176,7156) LDPC code is expurgated, shortened, and extended as described in 6.2.4. The parity check matrix for the (8176,7156) LDPC code is formed by using a 2 × 16 array of 511 × 511 square circulants. This creates a parity check matrix of dimension 1022 × 8176. The structure of the parity check base matrix is shown in figure 6-1.

$$\begin{bmatrix} A_{1,1} & A_{1,2} & A_{1,3} & A_{1,4} & A_{1,5} & A_{1,6} & A_{1,7} & A_{1,8} & A_{1,9} & A_{1,10} & A_{1,11} & A_{1,12} & A_{1,13} & A_{1,14} & A_{1,15} & A_{1,16} \\ A_{2,1} & A_{2,2} & A_{2,3} & A_{2,4} & A_{2,5} & A_{2,6} & A_{2,7} & A_{2,8} & A_{2,9} & A_{2,10} & A_{2,11} & A_{2,12} & A_{2,13} & A_{2,14} & A_{2,15} & A_{2,16} \end{bmatrix}$$

Figure 6-1: Base Parity Check Matrix of the (8176,7156) LDPC Code

Each $A_{i,j}$ is a 511 × 511 circulant. The row weight of each of the 32 circulants is two; i.e., there are two '1's in each row. The total row weight of each row in the parity check matrix is 2 × 16, or 32. The position of the '1's in the first row of each circulant is defined in table 6-1; each subsequent row is given by a right cyclic shift of the preceding row.

Table 6-1: Specification of Circulants

Circulant	‘1’s position in 1st row of circulant	Absolute ‘1’s position in 1st row of Parity Check Matrix
$A_{1,1}$	0, 176	0, 176
$A_{1,2}$	12, 239	523, 750
$A_{1,3}$	0, 352	1022, 1374
$A_{1,4}$	24, 431	1557, 1964
$A_{1,5}$	0, 392	2044, 2436
$A_{1,6}$	151, 409	2706, 2964
$A_{1,7}$	0, 351	3066, 3417
$A_{1,8}$	9, 359	3586, 3936
$A_{1,9}$	0, 307	4088, 4395
$A_{1,10}$	53, 329	4652, 4928
$A_{1,11}$	0, 207	5110, 5317
$A_{1,12}$	18, 281	5639, 5902
$A_{1,13}$	0, 399	6132, 6531
$A_{1,14}$	202, 457	6845, 7100
$A_{1,15}$	0, 247	7154, 7401
$A_{1,16}$	36, 261	7701, 7926
$A_{2,1}$	99, 471	99, 471
$A_{2,2}$	130, 473	641, 984
$A_{2,3}$	198, 435	1220, 1457
$A_{2,4}$	260, 478	1793, 2011
$A_{2,5}$	215, 420	2259, 2464
$A_{2,6}$	282, 481	2837, 3036
$A_{2,7}$	48, 396	3114, 3462
$A_{2,8}$	193, 445	3770, 4022
$A_{2,9}$	273, 430	4361, 4518
$A_{2,10}$	302, 451	4901, 5050
$A_{2,11}$	96, 379	5206, 5489
$A_{2,12}$	191, 386	5812, 6007
$A_{2,13}$	244, 467	6376, 6599
$A_{2,14}$	364, 470	7007, 7113
$A_{2,15}$	51, 382	7205, 7536
$A_{2,16}$	192, 414	7857, 8079

The numbers in the second column represent the relative column position of the ‘1’s in the first row of each circulant. Since there are only 511 possible positions, these numbers can range only from 0 to 510. The third column represents the absolute position of the ‘1’s in the parity check matrix. There are exactly 8176 possible; therefore these numbers can range only from 0 to 8175.

6.2.3 ENCODING

Two bits of information lie outside the structure of the quasi-cyclic encoder and increase complexity of the generator matrix for the basic (8176,7156) LDPC code. They are not included in this specification, which results in a generator matrix for a systematic (8176,7154) subcode that can be constructed entirely of circulants as shown in figure 6-2. The left portion is a 7154 x 7154 identity matrix, shown here as a block matrix, where I denotes the identity matrix of size 511 x 511, and 0 denotes the all-zero matrix of size 511 x 511. The right portion contains two columns of 511 x 511 circulants, denoted B*i,j*, and constructed with the algorithm below:

1) From figure 6-1 and table 6-1, define $\mathrm{D} = \begin{bmatrix} \mathrm{A}_{1,15} & \mathrm{A}_{1,16} \\ \mathrm{A}_{2,15} & \mathrm{A}_{2,16} \end{bmatrix}$, which is a 1022×1022 matrix.

2) Let *u* = (1 0 0 0 …. 0) be the unit 511 tuple, i.e., a vector quantity of length 511 with a ‘1’ at the leftmost position and ‘0’s in the rest.

3) Define $z_i = (b_{i,1} \quad b_{i,2})$, where *i* = 1, 2, …, 14 and the $b_{i,j}$s are the first row of the $\mathrm{B}_{i,j}$ circulants.

4) Define $\mathrm{M}_i = \begin{bmatrix} \mathrm{A}_{1,i} \\ \mathrm{A}_{2,i} \end{bmatrix}$, where *i* = 1, 2, …, 14. (The parity check matrix can now be represented as: [M_1 M_2 … M_{14} D].)

5) Since the rank of D is 1020 and not 1022, there are two linearly dependent columns, 511th and 1022nd. Set the 511th and 1022nd elements of z_i to zero and solve $\mathrm{M}_i u^{\mathrm{T}} + \mathrm{D} z_i^{\mathrm{T}} = 0$ for z_i, where *i* = 1, 2, …, 14 and T superscript represents matrix transpose.

6) The $b_{i,j}$s can be extracted from the z_is. (They are numerically tabulated in annex B.)

$$
\begin{bmatrix}
I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{1,1} & B_{1,2} \\
0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{2,1} & B_{2,2} \\
0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{3,1} & B_{3,2} \\
0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{4,1} & B_{4,2} \\
0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{5,1} & B_{5,2} \\
0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{6,1} & B_{6,2} \\
0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{7,1} & B_{7,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & B_{8,1} & B_{8,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & B_{9,1} & B_{9,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & B_{10,1} & B_{10,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & B_{11,1} & B_{11,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & B_{12,1} & B_{12,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & B_{13,1} & B_{13,2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & B_{14,1} & B_{14,2}
\end{bmatrix}
$$

Figure 6-2: Systematic Circulant Generator Matrix

6.2.4 MODIFIED (8160,7136) CODE

The generator matrix in 6.2.3 describes an (8176,7154) subcode of the (8176,7156) code defined by the parity check matrix in 6.2.2. This subcode is shortened and extended as follows to form an (8160,7136) code with parameters that are multiples of 32.

1) 18 zeros are prefixed to the 7136-bit message to be encoded, yielding a 7154-element row vector.

2) This vector is multiplied by the generator matrix of section 6.2.3, yielding an 8176-element vector consisting of 18 zeros, 7136 systematic message symbols, and 1022 parity symbols.

3) From this vector, the 18 leading zeros are discarded, and two zeros are appended, yielding a codeword of 8160 symbols.

NOTE – The arrangement of these 18 virtual fill bits, information bits, parity bits, and two zero-fill bits is shown in figure 6-3.

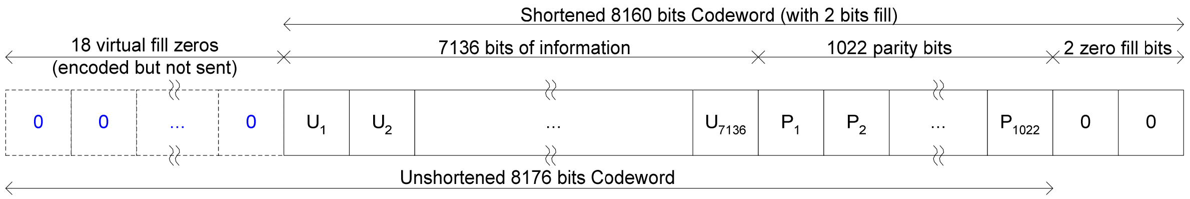

Figure 6-3: Shortened Codeword

6.3 LOW DENSITY PARITY CHECK CODE FAMILY OPTIMIZED FOR DEEP SPACE APPLICATIONS

6.3.1 DESCRIPTION OF THE CODES

Nine punctured LDPC codes are specified, with information block lengths *k*=1024 bits, 4096 bits, and 16384 bits, and code rates *r*=1/2, 2/3, and 4/5. These parameters and the corresponding codeword lengths, *n*=*k*/*r*, are shown in table 6-2.

All of these codes are used with the 64-bit ASM shown in figure 7-2.

Table 6-2: Codeblock Lengths for Supported Code Rates (Measured in Bits)

Information block length *k*	Code block length *n*		
	rate 1/2	rate 2/3	rate 4/5
1024	2048	1536	1280
4096	8192	6144	5120
16384	32768	24576	20480

Table 6-3: Values of Submatrix Size *M* for Supported Codes

Information block length *k*	Submatrix size *M*		
	rate 1/2	rate 2/3	rate 4/5
1024	512	256	128
4096	2048	1024	512
16384	8192	4096	2048

6.3.2 PARITY CHECK MATRICES

The parity check matrices are constructed from *M*×*M* submatrices, where the submatrix size is listed in table 6-3.

The parity check matrices for the rate-1/2 codes are specified as follows:

$$H_{1/2}=\begin{bmatrix} 0_M & 0_M & I_M & 0_M & I_M\oplus\Pi_1 \\ I_M & I_M & 0_M & I_M & \Pi_2\oplus\Pi_3\oplus\Pi_4 \\ I_M & \Pi_5\oplus\Pi_6 & 0_M & \Pi_7\oplus\Pi_8 & I_M \end{bmatrix}$$

where I_M and 0_M are the *M*×*M* identity and zero matrices, respectively, and Π_1 through Π_8 are permutation matrices. The parity check matrices for the rate-2/3 and rate-4/5 codes are specified with additional columns and permutation matrices as follows:

$$H_{2/3}=\left[\begin{array}{cc|c} 0_M & 0_M & \\ \Pi_9\oplus\Pi_{10}\oplus\Pi_{11} & I_M & H_{1/2} \\ I_M & \Pi_{12}\oplus\Pi_{13}\oplus\Pi_{14} & \end{array}\right]$$

$$H_{4/5}=\left[\begin{array}{cccc|c} 0_M & 0_M & 0_M & 0_M & \\ \Pi_{21}\oplus\Pi_{22}\oplus\Pi_{23} & I_M & \Pi_{15}\oplus\Pi_{16}\oplus\Pi_{17} & I_M & H_{2/3} \\ I_M & \Pi_{24}\oplus\Pi_{25}\oplus\Pi_{26} & I_M & \Pi_{18}\oplus\Pi_{18}\oplus\Pi_{20} & \end{array}\right]$$

Permutation matrix Π_k has non-zero entries in row *i* and column $\pi_k(i)$ for $i \in \{0,..., M\text{-}1\}$ and

$$\pi_k(i)=\frac{M}{4}\Big(\big(\theta_k+\lfloor 4i/M\rfloor\big)\bmod 4\Big)+\Big(\phi_k\big(\lfloor 4i/M\rfloor, M\big)+i\Big)\bmod\frac{M}{4}$$

where the functions θ_k and $\phi_k(j,M)$ are defined in table 6-4 and table 6-5. Values defined in these tables describe $\phi_k(j,M)$ s using 7-tuples where consecutive positions in a tuple correspond to submatrix sizes from the set *M*={128, 256, 512, 1024, 2048, 4096, 8192}. For each of the parity check matrices, the code symbols corresponding to the last *M* columns are punctured (not transmitted).

Table 6-4: Description of $\phi_k(0,M)$ and $\phi_k(1,M)$

		$\phi_k(0,M)$							$\phi_k(1,M)$						
		$M = 2^7 \dots 2^{13}$							$M = 2^7 \dots 2^{13}$						
k	θ_k														
1	3	1	59	16	160	108	226	1148	0	0	0	0	0	0	0
2	0	22	18	103	241	126	618	2032	27	32	53	182	375	767	1822
3	1	0	52	105	185	238	404	249	30	21	74	249	436	227	203
4	2	26	23	0	251	481	32	1807	28	36	45	65	350	247	882
5	2	0	11	50	209	96	912	485	7	30	47	70	260	284	1989
6	3	10	7	29	103	28	950	1044	1	29	0	141	84	370	957
7	0	5	22	115	90	59	534	717	8	44	59	237	318	482	1705
8	1	18	25	30	184	225	63	873	20	29	102	77	382	273	1083
9	0	3	27	92	248	323	971	364	26	39	25	55	169	886	1072
10	1	22	30	78	12	28	304	1926	24	14	3	12	213	634	354
11	2	3	43	70	111	386	409	1241	4	22	88	227	67	762	1942
12	0	8	14	66	66	305	708	1769	12	15	65	42	313	184	446
13	2	25	46	39	173	34	719	532	23	48	62	52	242	696	1456
14	3	25	62	84	42	510	176	768	15	55	68	243	188	413	1940
15	0	2	44	79	157	147	743	1138	15	39	91	179	1	854	1660
16	1	27	12	70	174	199	759	965	22	11	70	250	306	544	1661
17	2	7	38	29	104	347	674	141	31	1	115	247	397	864	587
18	0	7	47	32	144	391	958	1527	3	50	31	164	80	82	708
19	1	15	1	45	43	165	984	505	29	40	121	17	33	1009	1466
20	2	10	52	113	181	414	11	1312	21	62	45	31	7	437	433
21	0	4	61	86	250	97	413	1840	2	27	56	149	447	36	1345
22	1	19	10	1	202	158	925	709	5	38	54	105	336	562	867
23	2	7	55	42	68	86	687	1427	11	40	108	183	424	816	1551
24	1	9	7	118	177	168	752	989	26	15	14	153	134	452	2041
25	2	26	12	33	170	506	867	1925	9	11	30	177	152	290	1383
26	3	17	2	126	89	489	323	270	17	18	116	19	492	778	1790

Table 6-5: Description of $\phi_k(2,M)$ and $\phi_k(3,M)$

k	θ_k	$\phi_k(2,M)$							$\phi_k(3,M)$						
		$M = 2^7 \dots 2^{13}$							$M = 2^7 \dots 2^{13}$						
1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	12	46	8	35	219	254	318	13	44	35	162	312	285	1189
3	1	30	45	119	167	16	790	494	19	51	97	7	503	554	458
4	2	18	27	89	214	263	642	1467	14	12	112	31	388	809	460
5	2	10	48	31	84	415	248	757	15	15	64	164	48	185	1039
6	3	16	37	122	206	403	899	1085	20	12	93	11	7	49	1000
7	0	13	41	1	122	184	328	1630	17	4	99	237	185	101	1265
8	1	9	13	69	67	279	518	64	4	7	94	125	328	82	1223
9	0	7	9	92	147	198	477	689	4	2	103	133	254	898	874
10	1	15	49	47	54	307	404	1300	11	30	91	99	202	627	1292
11	2	16	36	11	23	432	698	148	17	53	3	105	285	154	1491
12	0	18	10	31	93	240	160	777	20	23	6	17	11	65	631
13	2	4	11	19	20	454	497	1431	8	29	39	97	168	81	464
14	3	23	18	66	197	294	100	659	22	37	113	91	127	823	461
15	0	5	54	49	46	479	518	352	19	42	92	211	8	50	844
16	1	3	40	81	162	289	92	1177	15	48	119	128	437	413	392
17	2	29	27	96	101	373	464	836	5	4	74	82	475	462	922
18	0	11	35	38	76	104	592	1572	21	10	73	115	85	175	256
19	1	4	25	83	78	141	198	348	17	18	116	248	419	715	1986
20	2	8	46	42	253	270	856	1040	9	56	31	62	459	537	19
21	0	2	24	58	124	439	235	779	20	9	127	26	468	722	266
22	1	11	33	24	143	333	134	476	18	11	98	140	209	37	471
23	2	11	18	25	63	399	542	191	31	23	23	121	311	488	1166
24	1	3	37	92	41	14	545	1393	13	8	38	12	211	179	1300
25	2	15	35	38	214	277	777	1752	2	7	18	41	510	430	1033
26	3	13	21	120	70	412	483	1627	18	24	62	249	320	264	1606

6.3.3 ENCODING

One method for producing codeblocks consistent with the parity-check matrices in 6.3.2 is to perform matrix multiplication by block-circulant generator matrices. This method defines the LDPC codes specified in this Recommended Standard.

This family of codes supports rates $K/(K+2)$, where $K=2$ for a rate 1/2 code, $K=4$ for rate 2/3, and $K=8$ for rate 4/5. Corresponding generator matrices, G, have size $MK \times M(K+3)$ if punctured columns are described in the encoding, or $MK \times M(K+2)$ if punctured columns are omitted. These matrices may be constructed as follows:

1) Let P be the $3M \times 3M$ submatrix of H consisting of the last $3M$ columns. Let Q be the $3M \times MK$ submatrix of H consisting of the first MK columns.

2) Compute $W = (P^{-1}Q)^T$, where the arithmetic is performed modulo-2.

Construct the matrix $G = \left[I_{MK} \quad W \right]$, where I_{MK} is the $MK \times MK$ identity matrix, and W is a dense matrix of circulants of size $MK \times 3M$. The last M columns of G correspond to the punctured code symbols.

7 FRAME SYNCHRONIZATION

7.1 INTRODUCTION

Frame or Codeblock synchronization is necessary for proper decoding of Reed-Solomon, ~~Codeblocks and~~ Turbo, and LDPC Codeblocks, and subsequent processing of the Transfer Frames. Furthermore, it is necessary for synchronization of the pseudo-random generator, if used (see section 8). It is also useful in assisting the node synchronization process of the Viterbi decoder for the convolutional code.

7.2 THE ATTACHED SYNC MARKER (ASM)

7.2.1 GENERAL

Synchronization of the Reed-Solomon, ~~or~~ Turbo, or LDPC Codeblock (or Transfer Frame, if the Physical Channel is not Reed-Solomon, ~~coded or~~ turbo, or LDPC coded) is achieved by using a stream of fixed-length Codeblocks (or Transfer Frames) with an Attached Sync Marker (ASM) between them. Synchronization is acquired on the receiving end by recognizing the specific bit pattern of the ASM in the Physical Channel data stream; synchronization is then customarily confirmed by making further checks.

7.2.2 ENCODER SIDE

7.2.2.1 If the Physical Channel is not Reed-Solomon, ~~coded or~~ turbo, or LDPC coded, the code symbols composing the ASM are attached directly to the Transfer Frame.

7.2.2.2 If the Physical Channel is Reed-Solomon, ~~coded or~~ turbo, or LDPC coded, the code symbols composing the ASM are attached directly to the encoder output without being encoded by the Reed-Solomon, ~~coded or~~ turbo, or LDPC code. If an inner convolutional code is used in conjunction with an outer Reed-Solomon code, the ASM is encoded by the inner code but not by the outer code. (See section 3.)

7.2.2.3 The data unit that consists of the ASM and the Transfer Frame (if the Physical Channel is not Reed-Solomon, ~~coded or~~ turbo, or LDPC coded) or the Reed-Solomon, ~~or~~ Turbo, or LDPC Codeblock (if the Physical Channel is Reed-Solomon, ~~coded or~~ turbo, or LDPC coded) is called the Channel Access Data Unit (CADU).

7.2.3 DECODER SIDE

For a concatenated Reed-Solomon and convolutional coding system, the ASM may be acquired either in the channel symbol domain (i.e., before any decoding) or in the domain of bits decoded by the inner code (i.e., the code symbol domain of the Reed-Solomon code). For a turbo or LDPC coding system, the ASM must be acquired in the channel symbol domain (i.e., the code symbol domain of the turbo or LDPC code).

7.3 ASM BIT PATTERNS

The ASM for data that is not turbo or LDPC coded shall consist of a 32-bit (4-octet) marker with a pattern shown in figure 7-1. The ASM for data that is turbo coded with nominal code rate *r* = 1/2, 1/3, 1/4, or 1/6 shall consist of a 32/*r*-bit (4/*r*-octet) marker with bit patterns shown in figures 7-2 through 7-5. The ASM for data that is LDPC coded with nominal code rate *r* = 7/8 shall consist of a 32-bit marker with bit pattern shown in figure 7-1; the ASM for data that is LDPC coded with code rate *r* = 1/2, 2/3, or 4/5 shall consist of a 64-bit marker with bit pattern shown in figure 7-2. The ASM bit patterns are represented in hexadecimal notation as:

ASM for ~~non-turbo-coded~~uncoded data, convolutional, Reed-Solomon, concatenated, and rate-7/8 LDPC coded data:	1ACFFC1D
ASM for rate-1/2 turbo and rates 1/2, 2/3, and 4/5 LDPC coded data:	034776C7272895B0
ASM for rate-1/3 turbo coded data:	25D5C0CE8990F6C9461BF79C
ASM for rate-1/4 turbo coded data:	034776C7272895B0 FCB88938D8D76A4F
ASM for rate-1/6 turbo coded data:	25D5C0CE8990F6C9461BF79C DA2A3F31766F0936B9E40863

```
FIRST TRANSMITTED BIT
(Bit 0)
↓
0001    1010    1100    1111    1111    1100    0001    1101
                                                           ↑
                                        LAST TRANSMITTED BIT
                                                    (Bit 31)
```

Figure 7-1: ASM Bit Pattern for ~~Non-Turbo-Coded~~Uncoded, Convolutional, Reed-Solomon, Concatenated, and Rate 7/8 LDPC Coded Data

```
FIRST TRANSMITTED BIT
(Bit 0)
↓
 0000001101000111011101101100011100100111001010001001010110110000
                                                                ↑
                                             LAST TRANSMITTED BIT
                                                         (Bit 63)
```

Figure 7-2: ASM Bit Pattern for ~~Turbo-Coded Data (for~~ Rate 1/2 Turbo ~~Code)~~and Rates 1/2, 2/3, and 4/5 LDPC Coded Data

```
FIRST TRANSMITTED BIT
(Bit 0)
↓
 001001011101010111000000110011101000100110010000111101101100100101000110000110111111011110011100
                                                                                                ↑
                                                                            LAST TRANSMITTED BIT
                                                                                        (Bit 95)
```

Figure 7-3: ASM Bit Pattern for ~~Turbo-Coded Data (for~~ Rate 1/3 Turbo ~~Code)~~Coded Data

```
FIRST TRANSMITTED BIT
(Bit 0)
↓
 0000001101000111011101101100011100100111001010001001010110110000
 1111110010111000100010010011100011011000110101110110101001001111
                                                                ↑
                                            LAST TRANSMITTED BIT
                                                       (Bit 127)
```

Figure 7-4: ASM Bit Pattern for ~~Turbo-Coded Data (for~~ Rate 1/4 Turbo ~~Code)~~Coded Data

```
FIRST TRANSMITTED BIT
(Bit 0)
↓
 001001011101010111000000110011101000100110010000111101101100100101000110000110111111011110011100
 110110100010101000111111001100010111011001101111000010010011011010111001111001000000100001100011
                                                                                                ↑
                                                                            LAST TRANSMITTED BIT
                                                                                       (Bit 191)
```

Figure 7-5: ASM Bit Pattern for ~~Turbo-Coded Data (for~~ Rate 1/6 Turbo ~~Code)~~Coded Data

7.4 LOCATION OF ASM

7.4.1 The ASM is attached to (i.e., shall immediately precede) the Reed-Solomon, ~~or~~ Turbo, or LDPC Codeblock, or to the Transfer Frame if the Physical Channel is not Reed-Solomon, ~~or~~ turbo, or LDPC coded.

7.4.2 The ASM for one Codeblock (or Transfer Frame) shall immediately follow the end of the preceding Codeblock (or Transfer Frame); i.e., there shall be no intervening bits (data or fill) preceding the ASM.

7.5 RELATIONSHIP OF ASM TO REED-SOLOMON, ~~AND~~ TURBO, AND LDPC CODEBLOCKS

7.5.1 The ASM is NOT a part of the encoded data space of the Reed-Solomon Codeblock, and it is not presented to the input of the Reed-Solomon encoder or decoder. This prevents the encoder from routinely regenerating a second, identical marker in the check symbol field under certain repeating data-dependent conditions (e.g., a test pattern of 01010101010 ... among others), which could cause synchronization difficulties at the receiving end. The relationship among the ASM, Reed-Solomon Codeblock, and Transfer Frame is illustrated in figure 4-2.

7.5.2 Similarly, the ASM is not presented to the input of the turbo encoder or decoder. It is directly attached to the Turbo Codeblock, as shown in figure 5-4.

7.5.3 Similarly, the ASM is not presented to the input of the LDPC encoder or decoder. It is directly attached to the LDPC Codeblock.

7.6 ASM FOR EMBEDDED DATA STREAM

7.6.1 A different ASM pattern (see figure 7-6) may be required where another data stream (e.g., a stream of Transfer Frames played back from a tape recorder in the forward direction) is inserted into the data field of the Transfer Frame of the main stream appearing on the communications channel. The ASM for the embedded data stream, to differentiate it from the main stream marker, shall consist of a 32-bit (4-octet) marker with a pattern as follows:

```
FIRST TRANSMITTED BIT
(Bit 0)
↓
0011  0101  0010  1110  1111  1000  0101  0011
                                             ↑
                           LAST TRANSMITTED BIT
                                       (Bit 31)
```

Figure 7-6: Embedded ASM Bit Pattern

7.6.2 This pattern is represented in hexadecimal notation as:

352EF853

8 PSEUDO-RANDOMIZER

8.1 INTRODUCTION

~~**8.1.1** In order to maintain bit (or symbol) synchronization with the received communications signal, every data capture system at the receiving end requires that the incoming signal have a minimum bit transition density (see recommendation 2.4.9 in reference [5]).~~

8.1.1 In order for the receiver system to work properly, every data capture system at the receiving end requires that the incoming signal have sufficient bit transition density (see recommendation 2.4.9 in reference [5]), and allow proper synchronization of the decoder. The incoming signal must also be free of unusual spectral characteristics, and be free of patterns that interfere with codeword synchronization and validation (see 2.2.2).

8.1.2 In order to ensure proper receiver operation, the data stream must be sufficiently random. The Pseudo-Randomizer defined in this section is the preferred method to ensure sufficient randomness for all combinations of CCSDS-recommended modulation and coding schemes. The Pseudo-Randomizer defined in this section is required unless the system designer verifies proper operation of the system if this Randomizer is not used.

NOTE – Problems with telemetry links have been encountered because this Pseudo-Randomizer was not used, and sufficient randomness was not ensured by other means and properly verified.

8.1.3 The presence or absence of pseudo-randomization is fixed for a Physical Channel and is *managed* (i.e., its presence or absence is not signaled in the transmitted data stream but must be known a priori) by the receiver.

8.2 PSEUDO-RANDOMIZER DESCRIPTION

8.2.1 The method for ensuring sufficient transitions is to exclusive-OR each bit of the Codeblock or Transfer Frame with a standard pseudo-random sequence.

8.2.2 If the pseudo-randomizer is used, on the sending end it is applied to the Codeblock or Transfer Frame after ~~turbo encoding or R-S~~Reed-Soloman, turbo, or LDPC encoding (if ~~either is~~any of these are used), but before convolutional encoding (if used). On the receiving end, it is applied to ~~derandomize~~de-randomize the data after convolutional decoding (if used) and codeblock synchronization but before Reed-Solomon, ~~decoding or~~ turbo, or LDPC decoding (if ~~either is~~any of these are used). These combinations are shown in figure 2-2.

NOTES

1 ‘~~Derandomization~~De-randomization’ consists of either: a) exclusive OR-ing the pseudo-random sequence with the received bits of a transfer frame or a Reed-

Solomon codeblock, *or* b) inverting (or not inverting), according to the pseudo-randomizer bit pattern, the demodulator output of a Turbo or LDPC Codeblock.

2 The configuration at the sending end is shown in figure 8-1.

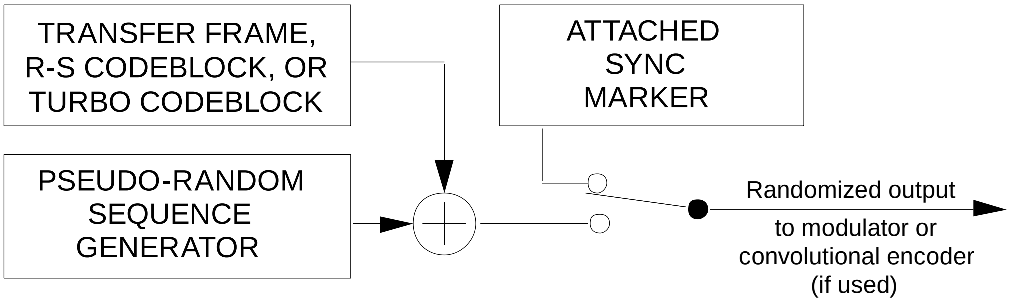
TRANSFER FRAME, R-S CODEBLOCK, OR TURBO CODEBLOCK
ATTACHED SYNC MARKER
PSEUDO-RANDOM SEQUENCE GENERATOR
Randomized output
to modulator or convolutional encoder (if used)

Figure 8-1: Pseudo-Randomizer Configuration

8.3 SYNCHRONIZATION AND APPLICATION OF PSEUDO-RANDOMIZER

8.3.1 The Attached Sync Marker (ASM) is already optimally configured for synchronization purposes and it is therefore used for synchronizing the pseudo-randomizer.

8.3.2 The pseudo-random sequence is applied starting with the first bit of the Codeblock or Transfer Frame. On the sending end, the Codeblock or Transfer Frame is randomized by exclusive-ORing the first bit of the Codeblock or Transfer Frame with the first bit of the pseudo-random sequence, followed by the second bit of the Codeblock or Transfer Frame with the second bit of the pseudo-random sequence, and so on.

8.3.3 On the receiving end, the original Codeblock or Transfer Frame is reconstructed using the same pseudo-random sequence. After locating the ASM in the received data stream, the pseudo-random sequence is exclusive-ORed with the data bits immediately following the ASM. The pseudo-random sequence is applied by exclusive-ORing the first bit following the ASM with the first bit of the pseudo-random sequence, followed by the second bit of the data stream with the second bit of the pseudo-random sequence, and so on.

8.3.4 The pseudo-random sequence shall NOT be exclusive-ORed with the ASM.

8.4 SEQUENCE SPECIFICATION

8.4.1 The pseudo-random sequence shall be generated using the following polynomial:

$$\mathrm{h}(x) = x^8 + x^7 + x^5 + x^3 + 1$$

8.4.2 This sequence begins at the first bit of the Codeblock or Transfer Frame and repeats after 255 bits, continuing repeatedly until the end of the Codeblock or Transfer Frame. The sequence generator is initialized to the all-ones state at the start of each Codeblock or Transfer Frame.

8.4.3 The first 40 bits of the pseudo-random sequence from the generator are shown below. The leftmost bit is the first bit of the sequence to be exclusive-ORed with the first bit of the Codeblock or Transfer Frame; the second bit of the sequence is exclusive-ORed with the second bit of the Codeblock or Transfer Frame, and so on.

1111 1111 0100 1000 0000 1110 1100 0000 1001 1010 . . . .

8.5 LOGIC DIAGRAM

Figure 8-2 represents a possible generator for the specified sequence.

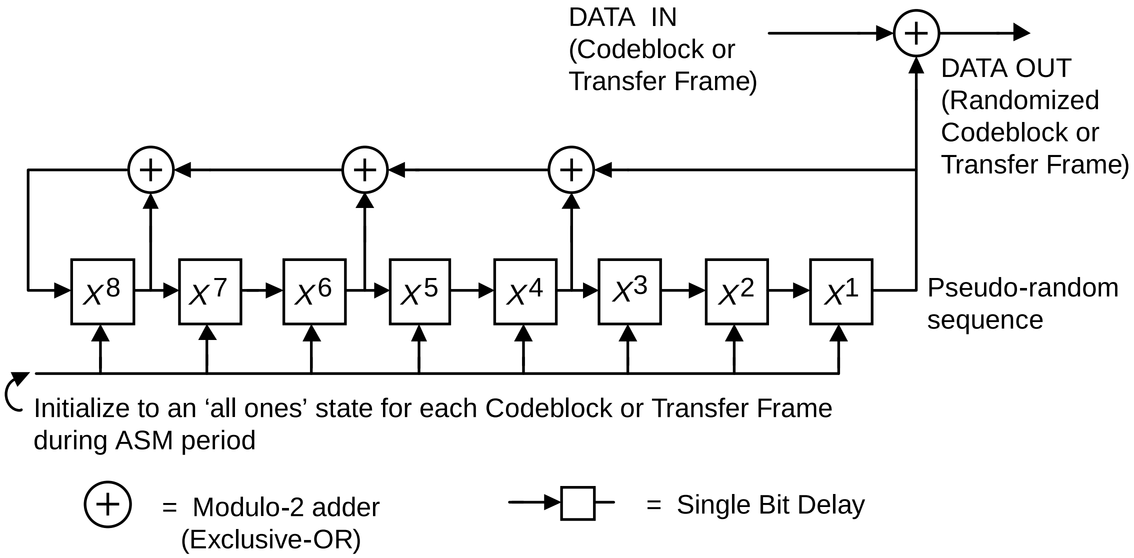

Figure 8-2: Pseudo-Randomizer Logic Diagram

9 TRANSFER FRAME LENGTHS

9.1 GENERAL

9.1.1 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.

9.1.2 The constraints on Transfer Frame lengths specified in this section apply to both TM Transfer Frames and the AOS Transfer Frames.

9.1.3 Once selected, the Transfer Frame length must be fixed for a Mission Phase on a particular Physical Channel.

NOTE – The Transfer Frame lengths shown here do not include the length of the Attached Sync Marker (ASM) specified in section 7.

9.2 CASE 1: UNCODED

The length of the Transfer Frames may be any integer number of octets, as required by the using project, with a maximum of 2048 octets.

9.3 CASE 2: CONVOLUTIONAL ONLY

The length of the Transfer Frames may be any integer number of octets, as required by the using project, with a maximum of 2048 octets.

9.4 CASE 3: REED-SOLOMON ONLY

9.4.1 With the Reed-Solomon Codes specified in section 4, only certain specific lengths of Transfer Frames may be contained within the codeblock's data space. In some cases these lengths may be shortened in discrete steps by using virtual fill at a small sacrifice in coding gain.

9.4.2 Since these R-S codes have a symbol length of 8 bits, the length of the codeblock (in octets) is a multiple of the interleaving depth, which provides 'octet compatibility'. If high-speed efficiency is needed for '32-bit compatibility' (with 32-bit processors, for example), then the length of the codeblock must be a combined multiple of 4 and the interleaving depth.

9.4.3 The following equation specifies allowed lengths for Transfer Frames (*L* in octets) when octet compatibility is sufficient:

$$L = (255\text{-}2E\text{-}q)\ I$$

such that *L* is a positive integer,

where *E* = error correction capability,

q = number of virtual fill symbols per R-S codeword, and

I = interleaving depth.

9.4.4 When 32-bit compatibility is required, the Transfer Frame length must be chosen so that it shall be expressed by the above equation and the codeblock length (255-*q*)*I* (in octets) shall be a multiple of 4.

9.5 CASE 4: CONCATENATED CODING

The allowable lengths of Transfer Frames when the concatenated (Reed-Solomon and convolutional) coding is used are the same as those for the Reed-Solomon only case (Case 3) shown in 9.4.

9.6 CASE 5: TURBO CODING

9.6.1 The Turbo Codes specified in section 5 of this ~~Recommendation~~Recommended Standard are block codes. Therefore, the Transfer Frame lengths must match the information block lengths for the selected turbo code.

9.6.2 Performance for only the following information block lengths (i.e., Transfer Frame lengths) has been validated by CCSDS and approved for use (values are in octets):

a) 223;

b) 446;

c) 892;

d) 1115;

e) 2048.

NOTE – Interleaver parameters for the length 2048 octets are under study by the CCSDS. Until finalized, use of this option is not recommended.

9.7 CASE 6: LDPC CODING

9.7.1 The LDPC Codes specified in section 6 of this Recommended Standard are block codes. Therefore, the Transfer Frame lengths must match the information block lengths for the selected LDPC code.

9.7.2 When the LDPC code optimized for near-Earth applications is used, the only allowable Transfer Frame length is 892 octets.

9.7.3 When the LDPC codes optimized for deep-space applications are used, the allowable Transfer Frame lengths are 128 octets, 512 octets, or 2048 octets.

10 MANAGED PARAMETERS

10.1 OVERVIEW OF MANAGED PARAMETERS

10.1.1 In order to conserve bandwidth on the space link, some parameters associated with synchronization and channel coding are handled by management rather than by inline communications protocol. The managed parameters are those which tend to be static for long periods of time, and whose change generally signifies a major reconfiguration of the synchronization and channel coding systems associated with a particular mission. Through the use of a management system, management conveys the required information to the synchronization and channel coding systems.

10.1.2 In this section, the managed parameters used by synchronization and channel coding systems are listed. These parameters are defined in an abstract sense and are not intended to imply any particular implementation of a management system.

10.1.3 All the managed parameters specified in this section shall be fixed for all Transfer Frames on a Physical Channel during a given Mission Phase.

10.1.4 When the Reed-Solomon or LDPC codes are not used, the Frame Error Control Field defined in references [1] or [2] shall be present.

NOTE – The presence or absence of the Frame Error Control Field is established by the management of the relevant Data Link Protocol. When the Reed-Solomon or LDPC codes are used, the Frame Error Control Field can still be present but no check is required by the decoding system.

10.1.5 If present, the Frame Error Control Field shall occur within every Transfer Frame transmitted within the same Physical Channel throughout a Mission Phase.

10.2 MANAGED PARAMETERS FOR SELECTED OPTIONS

Table 10-1 lists the managed parameters and shows the selected options for a particular Physical Channel.

Table 10-1: Managed Parameters for Selected Options

Managed Parameter	Allowed Values
~~Reed-Solomon Coding~~	~~Used, Not used~~
~~Turbo Coding~~	~~Used, Not used~~
~~Pseudo-~~Randomizer	~~Used, Not used~~None
Coding Method	Convolutional Reed-Solomon Convolutional + Reed-Solomon Turbo LDPC
~~Convolutional Coding~~	~~Used, Not used~~

10.3 MANAGED PARAMETERS FOR CONVOLUTIONAL CODING

Table 10-2 lists the managed parameters for convolutional coding.

Table 10-2: Managed Parameters for Convolutional Coding

Managed Parameter	Allowed Values
Code rate (*r*)	1/2, 2/3, 3/4, 5/6, 7/8

10.4 MANAGED PARAMETERS FOR REED-SOLOMON CODING

Table 10-3 lists the managed parameters for Reed-Solomon coding.

Table 10-3: Managed Parameters for Reed-Solomon Coding

Managed Parameter	Allowed Values
Error Correction Capability (*E*, symbols)	8, 16
Interleaving Depth (*I*)	1, 2, 3, 4, 5, 8
Virtual Fill Length (*Q*, symbols)	Integer

10.5 MANAGED PARAMETERS FOR TURBO CODING

Table 10-4 lists the managed parameters for turbo coding.

Table 10-4: Managed Parameters for Turbo Coding

Managed Parameter	Allowed Values
Nominal Code Rate (*r*)	1/2, 1/3, 1/4, 1/6
Information Block Length (*k,* bits)	1784, 3568, 7136, 8920, 16384

10.6 MANAGED PARAMETERS FOR LOW DENSITY PARITY CHECK CODING

Table 10-5 lists the managed parameters for low density parity check coding.

Table 10-5: Managed Parameters for Low Density Parity Check Coding

Managed Parameter	Allowed Values
Code Rate (*r*)	1/2, 2/3, 4/5, 223/255
Information Block Length (*k,* bits)	7136 (if *r*=223/255) 1024, 4096, 16384 (if *r*=1/2, 2/3, or 4/5)

10.7 MANAGED PARAMETERS FOR FRAME SYNCHRONIZATION

Table 10-6 lists the managed parameters for frame synchronization.

Table 10-6: Managed Parameters for Frame Synchronization

Managed Parameter	Allowed Values
Transfer Frame Length (bits)	Integer
ASM Length (bits)	32, 64, 96, 128, 192

NOTE – The ASM length is determined by the selected coding schemes.

11 SECURITY

11.1 SECURITY BACKGROUND

It is assumed that security is provided by encryption, authentication methods, and access control to be performed at higher layers (application and/or transport layers). Mission and service providers are expected to select from recommended security methods, suitable to the specific application profile. Specification of these security methods and other security provisions is outside the scope of this Recommended Standard. The coding layer has the objective of delivering data with the minimum possible amount of residual errors. An LDPC, Reed-Solomon, or other code with CRC code must be used to insure that residual errors are detected and the frame flagged. There is an extremely low probability of additional undetected errors that may escape this scrutiny. These errors may affect the encryption process in unpredictable ways, possibly affecting the decryption stage and producing data loss, but will not compromise the security of the data.

11.2 SECURITY CONCERNS

Security concerns in the areas of data privacy, authentication, access control, availability of resources, and auditing are to be addressed in higher layers and are not related to this Recommended Standard. The coding layer does not affect the proper functioning of methods used to achieve such protection at higher layers, except for undetected errors, as explained above.

The physical integrity of data bits is protected from channel errors by the coding systems specified in this Recommended Standard. In case of congestion or disruption of the link, the coding layer provides methods for frame re-synchronization.

11.3 POTENTIAL THREATS AND ATTACK SCENARIOS

An eavesdropper can receive and decode the codewords, but will not be able to get to the user data if proper encryption is performed at a higher layer. An interferer could affect the performance of the decoder by congesting it with unwanted data, but such data would be rejected by the authentication process. Such interference or jamming must be dealt with at the physical layer and through proper spectrum regulatory entities.

11.4 CONSEQUENCES OF NOT APPLYING SECURITY

There are no specific security measures prescribed for the coding layer. Therefore consequences of not applying security are only imputable to the lack of proper security measures in other layers. Residual undetected errors may produce additional data loss when the link carries encrypted data.

ANNEX A

SERVICE ~~DEFINITION~~

(NORMATIVE)

~~(This annex is part of the Recommendation.)~~

A1 GENERAL

A1.1 This annex provides service definition in the form of primitives, which present an abstract model of the logical exchange of data and control information between the service provider and the service user. The definitions of primitives are independent of specific implementation approaches.

A1.2 The parameters of the primitives are specified in an abstract sense and specify the information to be made available to the user of the primitives. The way in which a specific implementation makes this information available is not constrained by this specification. In addition to the parameters specified in this annex, an implementation may provide other parameters to the service user (e.g., parameters for controlling the service, monitoring performance, facilitating diagnosis, and so on).

A2 OVERVIEW OF THE SERVICE

A2.1 The TM Synchronization and Channel Coding provides unidirectional (one way) transfer of a sequence of fixed-length TM or AOS Transfer Frames at a constant rate over a Physical Channel across a space link, with optional error detection/correction.

A2.2 Only one user can use this service on a Physical Channel, and Transfer Frames from different users are not multiplexed together within one Physical Channel.

A3 SERVICE PARAMETERS

A3.1 FRAME

The Frame parameter is the service data unit of this service and shall be either a TM Transfer Frame defined in reference [1] or an AOS Transfer Frame defined in reference [2]. The length of any Transfer Frame transferred on a Physical Channel must be the same, and is established by management.

A3.2 QUALITY INDICATOR

The Quality Indicator is a parameter that is used to notify the user at the receiving end of the service that there is an uncorrectable error in the received Transfer Frame.

A3.3 SEQUENCE INDICATOR

The Sequence Indicator is a parameter that is used to notify the user at the receiving end of the service that one or more Transfer Frames of the Physical Channel have been lost as the result of a loss of frame synchronization.

A4 SERVICE PRIMITIVES

A4.1 GENERAL

A4.1.1 The service primitives associated with this service are:

a) ChannelAccess.request;

b) ChannelAccess.indication.

A4.1.2 The ChannelAccess.request primitive shall be passed from the service user at the sending end to the service provider to request that a Frame be transferred through the Physical Channel to the user at the receiving end.

A4.1.3 The ChannelAccess.indication is passed from the service provider to the service user at the receiving end to deliver a Frame.

A4.2 ChannelAccess.request

A4.2.1 Function

The ChannelAccess.request primitive is the service request primitive for this service.

A4.2.2 Semantics

The ChannelAccess.request primitive shall provide a parameter as follows:

ChannelAccess.request (Frame)

A4.2.3 When Generated

The ChannelAccess.request primitive is passed to the service provider to request it to process and send the Frame.

A4.2.4 Effect On Receipt

Receipt of the ChannelAccess.request primitive causes the service provider to perform the functions described in 2.3.1 and to transfer the resulting channel symbols.

A4.2.5 Additional Comments

The ChannelAccess.request primitive is used to perform the functions described in 2.3.1 and to transfer the resulting channel symbols over a Physical Channel across the space link.

A4.3 ChannelAccess.indication

A4.3.1 Function

The ChannelAccess.indication primitive is the service indication primitive for this service.

A4.3.2 Semantics

The ChannelAccess.indication primitive shall provide parameters as follows:

```
ChannelAccess.indication    (Frame,
                             Quality Indicator,
                             Sequence Indicator)
```

A4.3.3 When Generated

The ChannelAccess.indication primitive is passed from the service provider to the service user at the receiving end to deliver a Frame.

A4.3.4 Effect On Receipt

The effect of receipt of the ChannelAccess.indication primitive by the service user is undefined.

A4.3.5 Additional Comments

The ChannelAccess.indication primitive is used to perform the functions described in 2.3.2 and to deliver Transfer Frames of a Physical Channel to the service user.

ANNEX B

ANNEX TO SUBSECTION 6.2, LOW DENSITY PARITY CHECK CODE OPTIMIZED FOR NEAR-EARTH APPLICATIONS

(NORMATIVE)

B1 GENERATOR MATRIX CIRCULANT TABLE

Table B-1: Table of Circulants for the Generator Matrix

Circulant	1st row of circulant
$b_{1,1}$	55BF56CC55283DFEEFEA8C8CFF04E1EBD9067710988E25048D67525426939E206 8D2DC6FCD2F822BEB6BD96C8A76F4932AAE9BC53AD20A2A9C86BB461E43759C
$b_{1,2}$	6855AE08698A50AA3051768793DC238544AF3FE987391021AAF6383A6503409C3C E971A80B3ECE12363EE809A01D91204F1811123EAB867D3E40E8C652585D28
$b_{2,1}$	62B21CF0AEE0649FA67B7D0EA6551C1CD194CA77501E0FCF8C85867B9CF679C18B CF7939E10F8550661848A4E0A9E9EDB7DAB9EDABA18C168C8E28AACDDEAB1E
$b_{2,2}$	64B71F486AD57125660C4512247B229F0017BA649C6C11148FB00B70808286F1A97 90748D296A593FA4FD2C6D7AAF7750F0C71B31AEE5B400C7F5D73AAF00710
$b_{3,1}$	681A8E51420BD8294ECE13E491D618083FFBBA830DB5FAF330209877D801F92B5 E07117C57E75F6F0D873B3E520F21EAFD78C1612C6228111A369D5790F5929A
$b_{3,2}$	04DF1DD77F1C20C1FB570D7DD7A1219EAECEA4B2877282651B0FFE713DF338A6 3263BC0E324A87E2DC1AD64C9F10AAA585ED6905946EE167A73CF04AD2AF9218
$b_{4,1}$	35951FEE6F20C902296C9488003345E6C5526C5519230454C556B8A04FC0DC642D 682D94B4594B5197037DF15B5817B26F16D0A3302C09383412822F6D2B234E
$b_{4,2}$	7681CF7F278380E28F1262B22F40BF3405BFB92311A8A34D084C086464777431DBF DDD2E82A2E6742BAD6533B51B2BDEE0377E9F6E63DCA0B0F1DF97E73D5CD8
$b_{5,1}$	188157AE41830744BAE0ADA6295E08B79A44081E111F69BBE7831D07BEEBF76232 E065F752D4F218D39B6C5BF20AE5B8FF172A7F1F680E6BF5AAC3C4343736C2
$b_{5,2}$	5D80A6007C175B5C0DD88A442440E2C29C6A136BBCE0D95A58A83B48CA0E7474 E9476C92E33D164BFF943A61CE1031DFF441B0B175209B498394F4794644392E
$b_{6,1}$	60CD1F1C282A1612657E8C7C1420332CA245C0756F78744C807966C3E132643887 8BD2CCC83388415A612705AB192B3512EEF0D95248F7B73E5B0F412BF76DB4
$b_{6,2}$	434B697B98C9F3E48502C8DBD891D0A0386996146DEBEF11D4B833033E05EDC28 F808F25E8F314135E6675B7608B66F7FF3392308242930025DDC4BB65CD7B6E
$b_{7,1}$	766855125CFDC804DAF8DBE3660E8686420230ED4E049DF11D82E357C54FE256E A01F5681D95544C7A1E32B7C30A8E6CF5D0869E754FFDE6AEFA6D7BE8F1B148
$b_{7,2}$	222975D325A487FE560A6D146311578D9C5501D28BC0A1FB48C9BDA173E869133 A3AA9506C42AE9F466E85611FC5F8F74E439638D66D2F00C682987A96D8887C

Circulant	**1st row of circulant**
$b_{8,1}$	14B5F98E8D55FC8E9B4EE453C6963E052147A857AC1E08675D99A308E7269FAC5 600D7B155DE8CB1BAC786F45B46B523073692DE745FDF10724DDA38FD093B1C
$b_{8,2}$	1B71AFFB8117BCF8B5D002A99FEEA49503C0359B056963FE5271140E626F6F8FC E9F29B37047F9CA89EBCE760405C6277F329065DF21AB3B779AB3E8C8955400
$b_{9,1}$	0008B4E899E5F7E692BDCE69CE3FAD997183CFAEB2785D0C3D9CAE510316D4BD 65A2A06CBA7F4E4C4A80839ACA81012343648EEA8DBBA2464A68E115AB3F4034
$b_{9,2}$	5B7FE6808A10EA42FEF0ED9B41920F82023085C106FBBC1F56B567A14257021BC5 FDA60CBA05B08FAD6DC3B0410295884C7CCDE0E56347D649DE6DDCEEB0C95E
$b_{10,1}$	5E9B2B33EF82D0E64AA2226D6A0ADCD179D5932EE1CF401B336449D0FF775754C A56650716E61A43F963D59865C7F017F53830514306649822CAA72C152F6EB2
$b_{10,2}$	2CD8140C8A37DE0D0261259F63AA2A420A8F81FECB661DBA5C62DF6C817B4A61 D2BC1F068A50DFD0EA8FE1BD387601062E2276A4987A19A70B460C54F215E184
$b_{11,1}$	06F1FF249192F2EAF063488E267EEE994E7760995C4FA6FFA0E4241825A7F5B65C 74FB16AC4C891BC008D33AD4FF97523EE5BD14126916E0502FF2F8E4A07FC2
$b_{11,2}$	65287840D00243278F41CE1156D1868F24E02F91D3A1886ACE906CE741662B40B4 EFDFB90F76C1ADD884D920AFA8B3427EEB84A759FA02E00635743F50B942F0
$b_{12,1}$	4109DA2A24E41B1F375645229981D4B7E88C36A12DAB64E91C764CC43CCEC188E C8C5855C8FF488BB91003602BEF43DBEC4A621048906A2CDC5DBD4103431DB8
$b_{12,2}$	2185E3BC7076BA51AAD6B199C8C60BCD70E8245B874927136E6D8DD527DF0693 DC10A1C8E51B5BE93FF7538FA138B335738F4315361ABF8C73BF40593AE22BE4
$b_{13,1}$	228845775A262505B47288E065B23B4A6D78AFBDDB2356B392C692EF56A35AB4A A27767DE72F058C6484457C95A8CCDD0EF225ABA56B7657B7F0E947DC17F972
$b_{13,2}$	2630C6F79878E50CF5ABD353A6ED80BEACC7169179EA57435E44411BC7D566136 DFA983019F3443DE8E4C60940BC4E31DCEAD514D755AF95A622585D69572692
$b_{14,1}$	7273E8342918E097B1C1F5FEF32A150AEF5E11184782B5BD5A1D8071E94578B0AC 722D7BF49E8C78D391294371FFBA7B88FABF8CC03A62B940CE60D669DFB7B6
$b_{14,2}$	087EA12042793307045B283D7305E93D8F74725034E77D25D3FF043ADC5F8B5B18 6DB70A968A816835EFB575952EAE7EA4E76DF0D5F097590E1A2A978025573E

The numbers in the second column represent the hexadecimal representation of the first row of each circulant. Since there are only 511 possible positions, the leftmost bit is padded with a zero to allow a 128 digit hexadecimal number. Table B-1 cannot be as efficiently described as table 6-2 because the generator circulants do not have a low density of ‘1’s. All $B_{i,j}$ circulant shifting is done by a single right shift of the previous row.

ANNEX C

ACRONYMS AND TERMS

(INFORMATIVE)

~~(This annex **is not** part of the Recommendation)~~

C1 INTRODUCTION

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

C2 ACRONYMS

AOS	Advanced Orbiting Systems
ASM	Attached Sync Marker
CADU	Channel Access Data Unit
CCSDS	Consultative Committee For Space Data Systems
FECF	Frame Error Control Field
GF	Galois Field
LDPC	Low-Density Parity Check
MSB	Most Significant Bit
NRZ-L	Non-Return-to-Zero-Level
NRZ-M	Non-Return-to-Zero-Mark
OSI	Open Systems Interconnection
QPSK	Qua~~r~~drature Phase Shift Keying
R-S	Reed-Solomon
TC	Telecommand
TCM	Trellis Coded Modulation
TM	Telemetry
VCDU	Virtual Channel Data Unit

C3 TERMS

Block Encoding: A one-to-one transformation of sequences of length k of elements of a source alphabet to sequences of length n of elements of a code alphabet, $n>k$.

Synchronization and Channel Coding Sublayer: That sublayer of the Data Link Layer used by CCSDS space link protocols which uses a prescribed coding technique to reliably transfer Transfer Frames through the potentially noisy Physical Layer.

Channel Symbol: The unit of output of the innermost encoder.

~~**Codeblock**: A codeblock of an (n,k) block code is a sequence of n channel symbols which were produced as a unit by encoding a sequence of k information symbols, and will be decoded as a unit.~~

Codeblock: The aggregation of I codewords, where I is the interleaving depth. If $I=1$, the terms Codeblock and Codeword are used interchangeably.

Code Rate: The average ratio of the number of binary digits at the input of an encoder to the number of binary digits at its output.

Codeword: In a block code, one of the sequences in the range of the one-to-one transformation (see **Block Encoding**). A codeword of an (n,k) block code is a sequence of n channel symbols which are produced by encoding a sequence of k information symbols.

Concatenation: The use of two or more codes to process data sequentially with the output of one encoder used as the input of the next.

Connection Vector (Forward): In convolutional and turbo coding, a vector used to specify one of the parity checks to be computed by the shift register(s) in the encoder. For a shift register with s stages, a connection vector is an s-bit binary number. A bit equal to ‘one’ in position i (counted from the left) indicates that the output of the ith stage of the shift register is to be used in computing that parity check.

Connection Vector (Backward): In turbo coding, a vector used to specify the feedback to the shift registers in the encoder. For a shift register with s stages, a backward connection vector is an s-bit binary number. A bit equal to ‘one’ in position i (counted from the left) indicates that the output of the ith stage of the shift register is to be used in computing the feedback value, except for the leftmost bit which is ignored.

Constraint Length: In convolutional coding, the number of consecutive input bits that are needed to determine the value of the output symbols at any time.

Convolutional Code: As used in this document, a code in which a number of output symbols are produced for each input information bit. Each output symbol is a linear combination of the current input bit as well as some or all of the previous k-1 bits where k is the constraint length of the code.

Differential Encoding: a signaling technique used to resolve phase ambiguities with certain modulations, equivalent to NRZ-M signaling.

GF(*n*): The Galois Field consisting of exactly ‘*n*’ elements.

Inner Code: In a concatenated coding system, the last encoding algorithm that is applied to the data stream. The data stream here consists of the codewords generated by the outer decoder.

LDPC Code: An error correcting code with codewords taken as the set of vectors in the nullspace of a sparse matrix, called a low-density parity check matrix. In this document, modifications of such codes through puncturing, expurgation, etc., are also considered LDPC codes.

Modulating Waveform: A way of representing data bits (‘1’ and ‘0’) by a particular waveform.

NRZ-L: A ~~modulating waveform~~data format in which a data ‘one’ is represented by one of two levels, and a data ‘zero’ is represented by the other level.

NRZ-M: A ~~modulating waveform~~data format in which a data ‘one’ is represented by a change in level and a data ‘zero’ is represented by no change in level.

Outer Code: In a concatenated coding system, the first encoding algorithm that is applied to the data stream.

Punctured Code: As used in this document, a code obtained by deleting some of the parity symbols generated by the convolutional encoder before transmission. The bandwidth efficiency obtained by puncturing is increased compared to the original code, although the minimum weight (and therefore its error-correcting performance) will be less than that of the original code.

Reed-Solomon (R-S) Symbol: A set of *J* bits that represents an element in GF(2^J), the code alphabet of a *J*-bit Reed-Solomon code.

Systematic Code: A code in which the input information sequence appears in unaltered form as part of the output codeword.

Transparent Code: A code that has the property that complementing the input of the encoder or decoder results in complementing the output.

Trellis Termination: The operation of filling with zeros the *s* stages of each shift register used in the turbo encoder, after the end of the information block. During trellis termination the encoders continue to output encoded symbols for *s*-1 additional clock cycles.

Turbo Code: As used in this document, a block code formed by combining two component recursive convolutional codes. A turbo code takes as input a block of *k* information bits. The input block is sent unchanged to the first component code and bit-wise interleaved (see **Turbo Code Permutation**) to the second component code. The output is formed by the parity symbols contributed by each component code plus a replica of the information bits.

Turbo Code Permutation: A fixed bit-by-bit permutation of the entire input block of information bits performed by an interleaver, used in turbo codes.

Virtual Fill: In a systematic block code, a codeword can be divided into an information part and a parity (check) part. Suppose that the information part is ~~N~~k symbols long (a symbol is defined here to be an element of the code's alphabet) and that the parity part is ~~M~~n symbols long. A 'shortened' code is created by taking only S ($S <$ ~~N~~k) information symbols as input, appending a fixed string of length ~~N~~k-S and then encoding in the normal way. This fixed string is called 'fill'. Since the fill is a predetermined sequence of symbols, it need not be transmitted over the channel. Instead, the decoder appends the same fill sequence before decoding. In this case, the fill is called 'Virtual Fill'.

ANNEX D

INFORMATIVE REFERENCES

(INFORMATIVE)

~~(This annex **is not** part of the Recommendation)~~

~~[D1] *Procedures Manual for the Consultative Committee for Space Data Systems.* CCSDS A00.0-Y-8. Yellow Book. Issue 8. Washington, D.C.: CCSDS, July 2002.~~

~~[D2] *Telemetry Channel Coding.* Recommendation for Space Data Systems Standards, CCSDS 101.0-B-6. Blue Book. Issue 6. Washington, D.C.: CCSDS, October 2002.~~

~~[D3] *Advanced Orbiting Systems, Networks and Data Links: Architectural Specification.* Recommendation for Space Data System Standards, CCSDS 701.0-B-3. Blue Book. Issue 3. Washington, D.C.: CCSDS, June 2001.~~

[D1] *Procedures Manual for the Consultative Committee for Space Data Systems.* CCSDS A00.0-Y-9. Yellow Book. Issue 9. Washington, D.C.: CCSDS, November 2003.

[D2] *Telemetry Channel Coding.* Recommendation for Space Data System Standards, CCSDS 101.0-B-6-S. Historical Recommendation. Issue 6-S. Washington, D.C.: CCSDS, (October 2002) August 2005.

[D3] *Advanced Orbiting Systems, Networks and Data Links: Architectural Specification.* Recommendation for Space Data System Standards, CCSDS 701.0-B-3-S. Historical Recommendation. Issue 3-S. Washington, D.C.: CCSDS, (June 2001) August 2005.

[D4] M. Perlman and J. Lee. *Reed-Solomon Encoders—Conventional vs. Berlekamp's Architecture*. JPL Publication 82-71. Pasadena, California: NASA-Jet Propulsion Laboratory, December 1982.

[D5] *Low Density Parity Check Codes.* Draft Report Concerning Space Data System Standards, CCSDS TBD.-G-0. Proposed Green Book. Issue 0. Washington, D.C.: CCSDS, proposed.

NOTE – Normative references are listed in 1.7.

ANNEX E

TRANSFORMATION BETWEEN BERLEKAMP AND CONVENTIONAL REPRESENTATIONS

(INFORMATIVE)

~~(This annex **is not** part of the Recommendation)~~

E1 PURPOSE

This annex provides information to assist users of the Reed-Solomon code in this ~~Recommendation~~Recommended Standard to transform between the Berlekamp (dual basis) and Conventional representations. In addition, it shows where transformations are made to allow a conventional encoder to produce the dual basis representation on which this ~~Recommendation~~Recommended Standard is based.

E2 TRANSFORMATION

Referring to figure E-1, it can be seen that information symbols *I* entering and check symbols *C* emanating from the Berlekamp R-S encoder are interpreted as

$$[z_0, z_1, \ldots , z_7]$$

where the components z_i are coefficients of ℓ_i, respectively:

$$z_0\ell_0 + z_1\ell_1 + \ldots + z_7\ell_7$$

Information symbols I' entering and check symbols C' emanating from the conventional R-S encoder are interpreted as

$$[u_7, u_6, \ldots , u_0]$$

where the components u_j are coefficients of α^j, respectively:

$$u_7\alpha^7 + u_6\alpha^6 + \ldots + u_0$$

A pre- and post-transformation is required when employing a conventional R-S encoder.

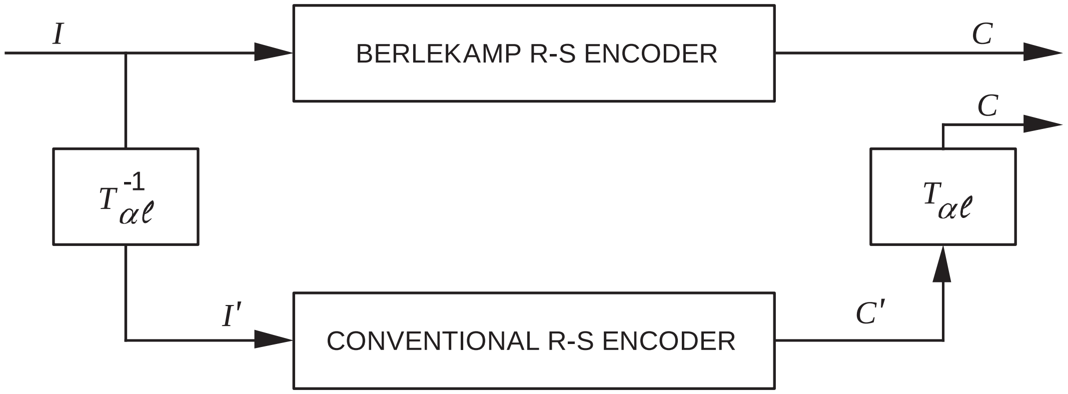

Figure E-1: Transformational Equivalence

Conventional and Berlekamp types of (255,k) Reed-Solomon encoders are assumed to have the same self-reciprocal generator polynomial whose coefficients appear in paragraph 4.2d) and e). The representation of symbols associated with the conventional encoder is the polynomials in 'α' appearing in table E-1. Corresponding to each polynomial in 'α' is the representation in the dual basis of symbols associated with the Berlekamp type encoder.

Given

$$\alpha^i = u_7\alpha^7 + u_6\alpha^6 + ... + u_0$$

where $0 \le i < 255$ (and α^* denotes the zero polynomial, $u_7, u_6, ... = 0, 0, ...$),

the corresponding element is

$$z = z_0\ell_0 + z_1\ell_1 + ... + z_7\ell_7$$

where

$$[z_0, z_1, ..., z_7] = [u_7, u_6, ..., u_0]\ T_{\alpha\ell}$$

and

$$T_{\alpha\ell} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \end{bmatrix}$$

Row 1, row 2, ... , and row 8 in $T_{\alpha\ell}$ are representations in the dual basis of α^7 (10 ... 0), α^6 (010 ... 0), ... , and α^0 (00 ... 01), respectively.

The inverse of $T_{\alpha\ell}$ is

$$T^{-1}_{\alpha\ell} = \begin{bmatrix} 1&1&0&0&0&1&0&1 \\ 0&1&0&0&0&0&1&0 \\ 0&0&1&0&1&1&1&0 \\ 1&1&1&1&1&1&0&1 \\ 1&1&1&1&0&0&0&0 \\ 0&1&1&1&1&0&0&1 \\ 1&0&1&0&1&1&0&0 \\ 1&1&0&0&1&1&0&0 \end{bmatrix}$$

Row 1, row 2, ... , and row 8 in $T^{-1}_{\alpha\ell}$ are polynomials in 'α' corresponding to ℓ_0 (10 ... 0), ℓ_1 (010 ... 0), ... , and ℓ_7 (00, ... 01), respectively. Thus,

$$[z_0, z_1, \ldots, z_7\,]\, T^{-1}_{\alpha\ell} = [u_7, u_6, \ldots, u_0]$$

Example 1:

Given information symbol I,

$$[z_0, z_1, \ldots, z_7] = 10111001$$

then

$$[1\;0\;1\;1\;1\;0\;0\;1]\; \overset{T^{-1}_{\alpha\ell}}{\begin{bmatrix} 1&1&0&0&0&1&0&1 \\ 0&1&0&0&0&0&1&0 \\ 0&0&1&0&1&1&1&0 \\ 1&1&1&1&1&1&0&1 \\ 1&1&1&1&0&0&0&0 \\ 0&1&1&1&1&0&0&1 \\ 1&0&1&0&1&1&0&0 \\ 1&1&0&0&1&1&0&0 \end{bmatrix}} = [u_7, u_6, \ldots, u_0] = 00101010 = I'$$

~~Note that t~~The arithmetic operations are reduced modulo 2. Also,

$$[z_0, z_1, \ldots, z_7] = 10111001$$

and

$$[u_7, u_6, \ldots, u_0] = 00101010\ (\alpha^{213})$$

are corresponding entries in table E-1.

Example 2:

Given check symbol C',

$$[\alpha_7, \alpha_6, ..., \alpha_0] = 01011001 \ (\alpha^{152})$$

Then,

$$[0\ 1\ 0\ 1\ 1\ 0\ 0\ 1] \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \end{bmatrix} = [z_0, z_1, ..., z_7] = 11101000 = C$$

Table E-1: Equivalence of Representations[1]

POWER	POLY IN ALPHA	$\ell_{01234567}$
*	00000000	00000000
0	00000001	01111011
1	00000010	10101111
2	00000100	10011001
3	00001000	11111010
4	00010000	10000110
5	00100000	11101100
6	01000000	11101111
7	10000000	10001101
8	10000111	11000000
9	10001001	00001100
10	10010101	11101001
11	10101101	01111001
12	11011101	11111100
13	00111101	01110010
14	01111010	11010000
15	11110100	10010001
16	01101111	10110100
17	11011110	00101000
18	00111011	01000100
19	01110110	10110011
20	11101100	11101101
21	01011111	11011110
22	10111110	00101011
23	11111011	00100110
24	01110001	11111110
25	11100010	00100001
26	01000011	00111011
27	10000110	10111011
28	10001011	10100011
29	10010001	01110000
30	10100101	10000011
31	11001101	01111010
32	00011101	10011110
33	00111010	00111111
34	01110100	00011100
35	11101000	01110100
36	01010111	00100100
37	10101110	10101101
38	11011011	11001010
39	00110001	00010001
40	01100010	10101100
41	11000100	11111011
42	00001111	10110111
43	00011110	01001010
44	00111100	00001001
45	01111000	01111111
46	11110000	00001000
47	01100111	01001110
48	11001110	10101110
49	00011011	10101000
50	00110110	01011100
51	01101100	01100000
52	11011000	00011110
53	00110111	00100111
54	01101110	11001111
55	11011100	10000111
56	00111111	11011101
57	01111110	01001001
58	11111100	01101011
59	01111111	00110010
60	11111110	11000100
61	01111011	10101011
62	11110110	00111110

[1] From table 4 of reference [D4]. Note: Coefficients of the 'Polynomial in Alpha' column are listed in descending powers of α, starting with α^7.

Table E-1: Equivalence of Representations (continued)

POWER	POLY IN ALPHA	$\ell_{01234567}$
63	01101011	00101101
64	11010110	11010010
65	00101011	11000010
66	01010110	01011111
67	10101100	00000010
68	11011111	01010011
69	00111001	11101011
70	01110010	00101010
71	11100100	00010111
72	01001111	01011000
73	10011110	11000111
74	10111011	11001001
75	11110001	01110011
76	01100101	11100001
77	11001010	00110111
78	00010011	01010010
79	00100110	11011010
80	01001100	10001100
81	10011000	11110001
82	10110111	10101010
83	11101001	00001111
84	01010101	10001011
85	10101010	00110100
86	11010011	00110000
87	00100001	10010111
88	01000010	01000000
89	10000100	00010100
90	10001111	00111010
91	10011001	10001010
92	10110101	00000101
93	11101101	10010110
94	01011101	01110001
95	10111010	10110010
96	11110011	11011100
97	01100001	01111000
98	11000010	11001101
99	00000011	11010100
100	00000110	00110110
101	00001100	01100011
102	00011000	01111100
103	00110000	01101010
104	01100000	00000011
105	11000000	01100010
106	00000111	01001101
107	00001110	11001100
108	00011100	11100101
109	00111000	10010000
110	01110000	10000101
111	11100000	10001110
112	01000111	10100010
113	10001110	01000001
114	10011011	00100101
115	10110001	10011100
116	11100101	01101100
117	01001101	11110111
118	10011010	01011110
119	10110011	00110011
120	11100001	11110101
121	01000101	00001101
122	10001010	11011000
123	10010011	11011111
124	10100001	00011010
125	11000101	10000000
126	00001101	00011000

Table E-1: Equivalence of Representations (continued)

POWER	POLY IN ALPHA	ℓ01234567	POWER	POLY IN ALPHA	ℓ01234567
127	00011010	11010011	159	10000101	01101111
128	00110100	11110011	160	10001101	10010101
129	01101000	11111001	161	10011101	00010011
130	11010000	11100100	162	10111101	11111111
131	00100111	10100001	163	11111101	00010000
132	01001110	00100011	164	01111101	10011101
133	10011100	01101000	165	11111010	01011101
134	10111111	01010000	166	01110011	01010001
135	11111001	10001001	167	11100110	10111000
136	01110101	01100111	168	01001011	11000001
137	11101010	11011011	169	10010110	00111101
138	01010011	10111101	170	10101011	01001111
139	10100110	01010111	171	11010001	10011111
140	11001011	01001100	172	00100101	00001110
141	00010001	11111101	173	01001010	10111010
142	00100010	01000011	174	10010100	10010010
143	01000100	01110110	175	10101111	11010110
144	10001000	01110111	176	11011001	01100101
145	10010111	01000110	177	00110101	10001000
146	10101001	11100000	178	01101010	01010110
147	11010101	00000110	179	11010100	01111101
148	00101101	11110100	180	00101111	01011011
149	01011010	00111100	181	01011110	10100101
150	10110100	01111110	182	10111100	10000100
151	11101111	00111001	183	11111111	10111111
152	01011001	11101000	184	01111001	00000100
153	10110010	01001000	185	11110010	10100111
154	11100011	01011010	186	01100011	11010111
155	01000001	10010100	187	11000110	01010100
156	10000010	00100010	188	00001011	00101110
157	10000011	01011001	189	00010110	10110000
158	10000001	11110110	190	00101100	10001111

Table E-1: Equivalence of Representations (continued)

POWER	POLY IN ALPHA	$\ell_{01234567}$
191	01011000	10010011
192	10110000	11100111
193	11100111	11000011
194	01001001	01101110
195	10010010	10100100
196	10100011	10110101
197	11000001	00011001
198	00000101	11100010
199	00001010	01010101
200	00010100	00011111
201	00101000	00010110
202	01010000	01101001
203	10100000	01100001
204	11000111	00101111
205	00001001	10000001
206	00010010	00101001
207	00100100	01110101
208	01001000	00010101
209	10010000	00001011
210	10100111	00101100
211	11001001	11100011
212	00010101	01100100
213	00101010	10111001
214	01010100	11110000
215	10101000	10011011
216	11010111	10101001
217	00101001	01101101
218	01010010	11000110
219	10100100	11111000
220	11001111	11010101
221	00011001	00000111
222	00110010	11000101
223	01100100	10011010
224	11001000	10011000
225	00010111	11001011
226	00101110	00100000
227	01011100	00001010
228	10111000	00011101
229	11110111	01000101
230	01101001	10000010
231	11010010	01001011
232	00100011	00111000
233	01000110	11011001
234	10001100	11101110
235	10011111	10111100
236	10111001	01100110
237	11110101	11101010
238	01101101	00011011
239	11011010	10110001
240	00110011	10111110
241	01100110	00110101
242	11001100	00000001
243	00011111	00110001
244	00111110	10100110
245	01111100	11100110
246	11111000	11110010
247	01110111	11001000
248	11101110	01000010
249	01011011	01000111
250	10110110	11010001
251	11101011	10100000
252	01010001	00010010
253	10100010	11001110
254	11000011	10110110

ANNEX F

EXPANSION OF REED-SOLOMON COEFFICIENTS

(INFORMATIVE)

~~(This annex **is not** part of the Recommendation)~~

Purpose:

While the equations given in the Reed-Solomon Coding section of this ~~Recommendation~~Recommended Standard are fully specifying, this annex provides additional assistance for those implementing either the *E* = 16 or the *E* = 8 code.

For *E* = 16:

COEFFICIENTS OF *g*(*x*)	**POLYNOMIAL IN α**							
	α^7	α^6	α^5	α^4	α^3	α^2	α^1	α^0
$G_0 = G_{32} = \alpha^0$	0	0	0	0	0	0	0	1
$G_1 = G_{31} = \alpha^{249}$	0	1	0	1	1	0	1	1
$G_2 = G_{30} = \alpha^{59}$	0	1	1	1	1	1	1	1
$G_3 = G_{29} = \alpha^{66}$	0	1	0	1	0	1	1	0
$G_4 = G_{28} = \alpha^4$	0	0	0	1	0	0	0	0
$G_5 = G_{27} = \alpha^{43}$	0	0	0	1	1	1	1	0
$G_6 = G_{26} = \alpha^{126}$	0	0	0	0	1	1	0	1
$G_7 = G_{25} = \alpha^{251}$	1	1	1	0	1	0	1	1
$G_8 = G_{24} = \alpha^{97}$	0	1	1	0	0	0	0	1
$G_9 = G_{23} = \alpha^{30}$	1	0	1	0	0	1	0	1
$G_{10} = G_{22} = \alpha^3$	0	0	0	0	1	0	0	0
$G_{11} = G_{21} = \alpha^{213}$	0	0	1	0	1	0	1	0
$G_{12} = G_{20} = \alpha^{50}$	0	0	1	1	0	1	1	0
$G_{13} = G_{19} = \alpha^{66}$	0	1	0	1	0	1	1	0
$G_{14} = G_{18} = \alpha^{170}$	1	0	1	0	1	0	1	1
$G_{15} = G_{17} = \alpha^5$	0	0	1	0	0	0	0	0
$G_{16} = \alpha^{24}$	0	1	1	1	0	0	0	1

NOTE – $G_3 = G_{29} = G_{13} = G_{19}$.

Further information, including encoder block diagrams, is provided in reference [D4].

For $E = 8$:

COEFFICIENTS OF *g*(*x*)					**POLYNOMIAL IN α**							
					α^7	α^6	α^5	α^4	α^3	α^2	α^1	α^0
G_0	=	G_{16}	=	α^0	0	0	0	0	0	0	0	1
G_1	=	G_{15}	=	α^{30}	1	0	1	0	0	1	0	1
G_2	=	G_{14}	=	α^{230}	0	1	1	0	1	0	0	1
G_3	=	G_{13}	=	α^{49}	0	0	0	1	1	0	1	1
G_4	=	G_{12}	=	α^{235}	1	0	0	1	1	1	1	1
G_5	=	G_{11}	=	α^{129}	0	1	1	0	1	0	0	0
G_6	=	G_{10}	=	α^{81}	1	0	0	1	1	0	0	0
G_7	=	G_9	=	α^{76}	0	1	1	0	0	1	0	1
		G_8	=	α^{173}	0	1	0	0	1	0	1	0

ANNEX G

CHANGES FROM REFERENCES [D2] AND [D3]

(INFORMATIVE)

~~(This annex **is not** part of the Recommendation)~~

G1 GENERAL

This ~~Recommendation~~Recommended Standard was developed from the specifications regarding synchronization and channel coding in older CCSDS ~~Recommendation~~Recommended Standards (references [D2] and [D3]), but a few technical specifications in references [D2] and [D3] have been changed in order to define all Space Data Link Protocols in a unified way. These technical changes are described in ~~subsection~~ G2. Also, some technical terms in references [D2] and [D3] have been changed in order to unify the terminology used in all the CCSDS ~~Recommendation~~Recommended Standards that define space link protocols, as well as to define these schemes as general communications schemes. These terminology changes are listed in G3.

G2 TECHNICAL CHANGES

G2.1 PARAMETERS ASSOCIATED WITH TRANSFER FRAME LENGTH

In references [D2] and [D3], the periods during which the value of parameters shall be fixed are not consistently specified. In this ~~Recommendation~~Recommended Standard, any parameter associated with the length of the Transfer Frame shall be fixed for a Mission Phase on a particular Physical Channel.

G2.2 TRANSFER FRAME LENGTHS

The constraints on Virtual Channel Data Unit (VCDU) (AOS Transfer Frame) lengths specified in reference [D3] were different from those on TM Transfer Frame lengths specified in reference [D2]. In this ~~Recommendation~~Recommended Standard, the same constraints are applied to both types of Transfer Frames.

G3 TERMINOLOGY CHANGES

Tables G-1 and G-2 list the terms that have been changed from references [D2] and [D3], respectively.

Table G-1: Terms That Have Been Changed from Reference [D2]

Terms Used in Reference [D2]	Terms Used in This ~~Recommendation~~Recommended Standard
Telemetry Transfer Frame	TM Transfer Frame

Table G-2: Terms That Have Been Changed from Reference [D3]

Terms Used in Reference [D3]	Terms Used in This ~~Recommendation~~Recommended Standard
PCA_PDU	Channel Symbols
Virtual Channel Data Unit (VCDU)	AOS Transfer Frame