The Consultative Committee for Space Data Systems

Research and Development for
Space Data System Standards

REED-SOLOMON PRODUCT CODE FOR OPTICAL COMMUNICATION

EXPERIMENTAL SPECIFICATION

CCSDS 142.10-O-1

ORANGE BOOK
October 2023

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PREFACE

This document is a CCSDS Experimental Specification. Its Experimental status indicates that it is part of a research or development effort based on prospective requirements, and as such it is not considered a Standards Track document. Experimental Specifications are intended to demonstrate technical feasibility in anticipation of a 'hard' requirement that has not yet emerged. Experimental work may be rapidly transferred onto the Standards Track should a hard requirement emerge in the future.

DOCUMENT CONTROL

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this Experimental Specification is to specify channel coding and synchronization schemes for free-space optical communications systems used by space missions. The applications addressed with this Experimental Specification include space-to-space, space-to-ground, and ground-to-space links in which optical communications using an optical on-off keying modulated carrier wavelength of around 1550 nm are employed. This Experimental Specification assumes the Physical Layer specification outlined in reference [1], section 5. When provided with a set of fixed-length, fixed-rate CCSDS Transfer Frames produced by the data link protocol sublayer (as specified, for example, in references [2] and [3]) or potentially variable-length, variable-rate transfer frames, which may be defined by CCSDS (specified, for example, in reference [5]) or by other methods, this Experimental Specification describes the channel coding and synchronization characteristics, assuming the Physical Layer specification outlined in reference [1], section 5.

1.2 SCOPE

This Experimental Specification defines the coding and synchronization sublayer scheme (section 3) in terms of the signal characteristics and procedures involved in the encoding and synchronization of optical signals. 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 Experimental Specification may be used in the creation of agency standards and applies to the future data communications over optical space links between CCSDS Agencies in cross-support situations. It includes comprehensive specifications for the data formats and procedures for interagency cross support. It is neither a specification for, nor a design for, real systems that may be implemented for existing or future missions.

The Experimental Specification described in this document may be invoked through the normal standards program of each CCSDS Agency and is applicable to those missions for which cross support based on capabilities described in this Experimental Specification is anticipated. Where mandatory capabilities are clearly indicated in sections of this Experimental Specification, 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

This Experimental Specification facilitates cross support at the coding and synchronization sublayer of optical communications systems used by CCSDS Member Agencies. Such cross support requires specification of the slicing of transfer frames, synchronization markers, channel encoding, channel interleaving, and other details of the coding and synchronization sublayer.

The CCSDS believes it is important to document the rationale underlying the recommendations chosen, so that future evaluations of proposed changes or improvements will take previous decisions into account. Where appropriate, rationale has been included in the description of the signaling characteristics.

1.5 DOCUMENT STRUCTURE

This document is divided into five numbered sections and three annexes.

a) Section 1 presents the purpose, scope, applicability, rationale, document structure, nomenclature, conventions, and references;

b) Section 2 provides an overview of the architecture and summary of functions of the optical coding and synchronization sublayer;

c) Section 3 specifies the Reed-Solomon Product Code (RS-PC) optical coding and synchronization sublayer;

d) Section 4 lists the managed parameters;

e) Annex A lists acronyms terms used in this document;

f) Annex B describes the simulation results of an RS-PC implementation; and

g) Annex C provides a list of informative references.

1.6 NOMENCLATURE

1.6.1 NORMATIVE TEXT

The following conventions apply throughout this specification:

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.

1.6.2 INFORMATIVE TEXT

In the normative sections of this document, informative text is set off from the normative specifications either in notes or under one of the following subsection headings:

– Overview;

– Background;

– Rationale;

– Discussion.

1.7 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, that is, ‘Bit 0’ (see figure 1-1).

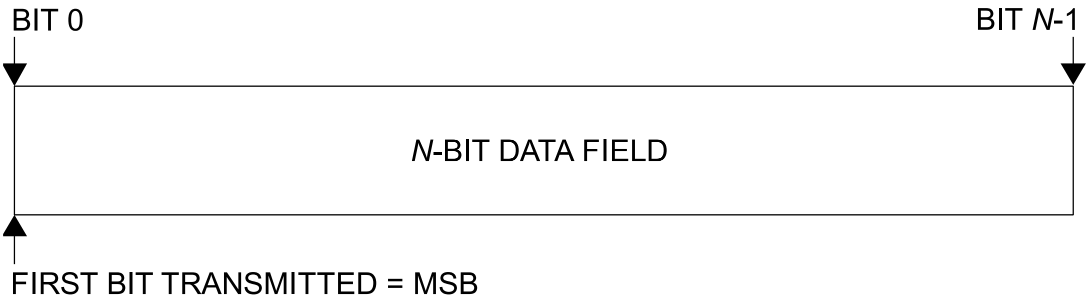

Figure 1-1: Bit Numbering Convention

In accordance with standard data-communications practice, data fields are often grouped into 8-bit ‘words’, which conform to the above convention. Throughout this specification, such an 8-bit word is called an ‘octet’. The numbering for octets within a data structure starts with ‘0’.

NOTE – Throughout this document, ‘bit’ refers to the contents of the transfer frames. A bit is a binary digit transferred between the data link protocol sublayer and the coding and synchronization sublayer. Other symbols, whether binary or nonbinary, will be referred to by other names, such as ‘binary digits’. It should be understood that the ordering conventions described above apply equally to other types of symbols.

1.8 REFERENCES

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

[1] *Optical Communications Physical Layer*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 141.0-B-2. Forthcoming.

[2] *TM Space Data Link Protocol*. Issue 3. Recommendation for Space Data System Standards (Blue Book), CCSDS 132.0-B-3. Washington, D.C.: CCSDS, October 2021.

[3] *AOS Space Data Link Protocol*. Issue 4. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.0-B-4. Washington, D.C.: CCSDS, October 2021.

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

[5] *Unified Space Data Link Protocol*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.1-B-2. Washington, D.C.: CCSDS, October 2021.

[6] *Generic Framing Procedure*. ITU-T Recommendation G.7041/Y.1303 (08/16). Geneva: ITU, August 2016.

[7] *TM Synchronization and Channel Coding*. Issue 4. Recommendation for Space Data System Standards (Blue Book), CCSDS 131.0-B-4. Washington, D.C.: CCSDS, April 2022.

2 OVERVIEW

2.1 ARCHITECTURAL CONSIDERATIONS

This Experimental Specification aims to address coding and synchronization using RS-PC for a variety of short-distance (typically up to 5,000 km) optical communications link applications, such as Low Earth Orbit (LEO) spacecraft to Earth communication, LEO to LEO optical links, and so on. This Experimental Specification supports operation of such links at user rates of 100 Mb/s to 10 Gb/s. This Experimental Specification focuses on short-distance optical communication, but it could also apply to optical communication scenarios involving longer distances.

2.2 LAYER ARCHITECTURE

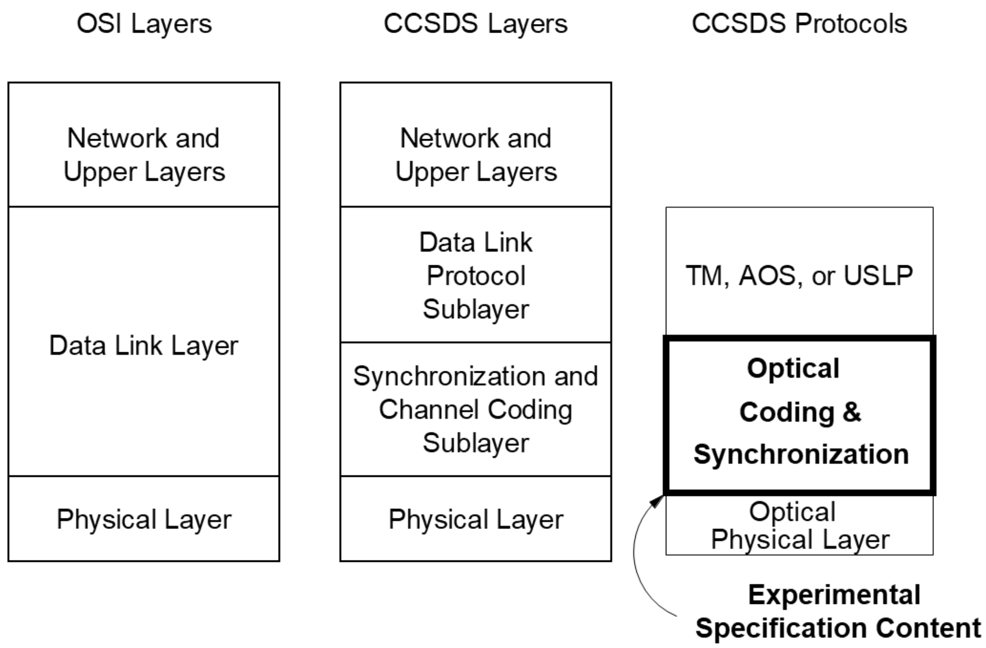

Figure 2-1: Relationship with OSI Layers

Figure 2-1 illustrates the relationship of this Experimental Specification to the Open Systems Interconnection (OSI) reference model (reference [4]). Two sublayers of the Data Link Layer are defined for CCSDS space link protocols. The data link protocol sublayer provides functions for producing transfer frames; examples include the Telemetry (TM) Space Data Link Protocol (reference [2]) and the Advanced Orbiting Systems (AOS) Space Data Link Protocol (reference [3]). The optical coding and synchronization protocol specified in this Experimental Specification provides the functions of the synchronization and channel coding sublayer of the Data Link Layer over an optical space link.

3 CODING AND SYNCHRONIZATION

3.1 OVERVIEW

The scheme described in this Experimental Specification operates by taking transfer frames and producing a modulated optical carrier for transmission. This section of the Experimental Specification describes the coding and synchronization sublayer, which produces a binary vector for transmission based on an input stream of transfer frames. The functional blocks of the coding and synchronization signaling architecture are shown in figure 3-1.

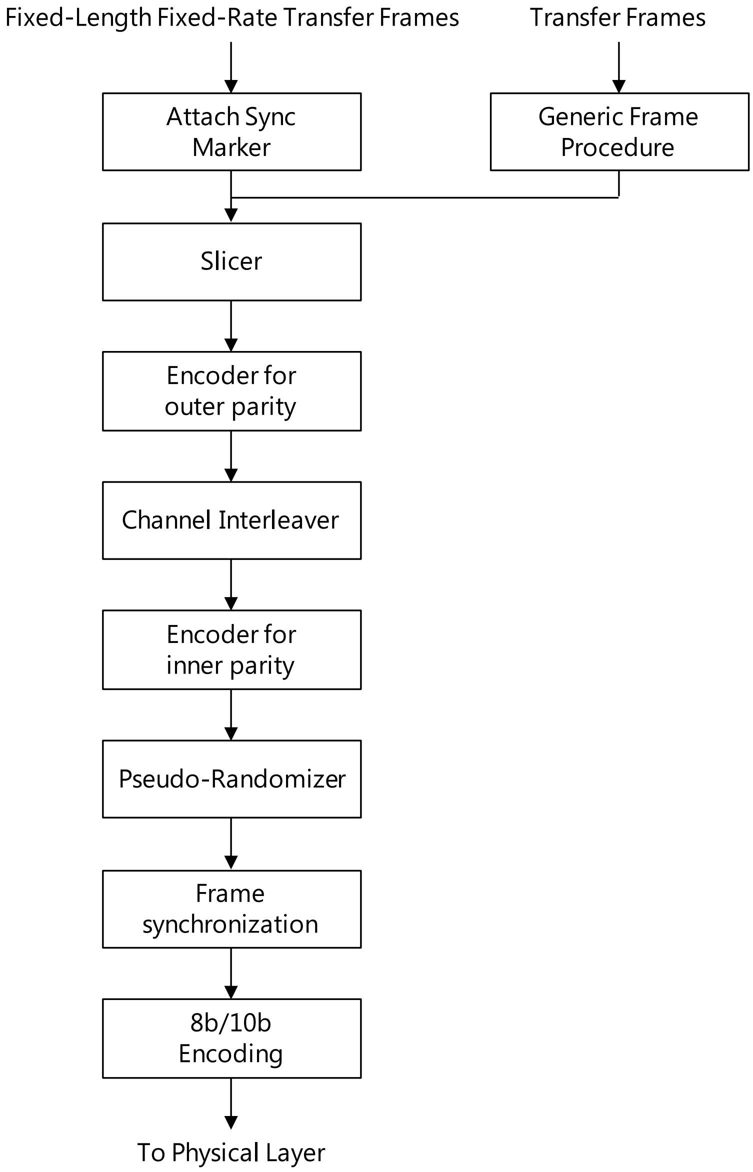

Figure 3-1: Functional Diagram for Coding and Synchronization Signaling

3.2 INPUT TRANSFER FRAMES

3.2.1 The input to the coding and synchronization sublayer shall be a sequence of transfer frames.

3.2.2 The transfer frames may conform to the structure as defined in references [2], [3], or [5], or they may be octet-aligned transfer frames defined by other standards or methods.

3.2.3 The sequence of frames is denoted

$$\boldsymbol{a}^0,\ \boldsymbol{a}^1,\ \ldots,\boldsymbol{a}^{A-1};$$

and for $i \in \{0, 1, \ldots,\ A-1\}$, the i^{th} transfer frame is denoted

$$\boldsymbol{a}^i = a_0^i,\ a_1^i, \ldots,\ a_{T_i-1}^i,$$

where $a_j^i \in \{0, 1\}$ is the j^{th} bit of the i^{th} frame, and T_i is the number of bits in the i^{th} frame.

NOTES

1 This integrated approach for space data link encoding enables arbitrary transfer frame types to be ingested by the coding and synchronization sublayer, including CCSDS transfer frames such as TM, AOS, and Unified Space Data Link Protocol (USLP), as well as non-CCSDS transfer frame (protocol data unit) types such as Internet Protocol/Point-to-Point Protocol (IP/PPP) or Ethernet media access control frames defined in clause 3.1 of reference [C1].

2 Fixed length transfer frame types can be encapsulated by utilizing the Attached Synchronization Marker (ASM) described in 3.3.2.

3 Either fixed or variable length transfer frame types can be encapsulated using the Generic Frame Procedure (GFP) explained in 3.3.3. These types include not only CCSDS transfer frames, but also non-CCSDS transfer frame types (such as Ethernet, PPP, run-length-encoded High-Level Data Link Control [HDLC], Digital Video Broadcasting [DVB], etc.).

4 The encoding described in this subsection can be performed in a streaming fashion; that is, not all *A* transfer frames of a full communications session need be available at the time encoding is begun, and the value of *A* need not be known a priori.

3.3 SYNCHRONIZATION-MARKED TRANSFER FRAMES

3.3.1 GENERAL

Synchronization-Marked Transfer Frames (SMTFs) shall be formed using either the method described in 3.3.2, or the method described in 3.3.3. If the transfer frames are variable length, then the method described in 3.3.3 shall be used.

3.3.2 ATTACHED SYNCHRONIZATION MARKER

3.3.2.1 Attachment Method

A 32-binary-digit Attached Synchronization Marker (ASM) shall be prepended to each transfer frame, resulting in an SMTF, as follows: For $i \in \{0, 1, \ldots, A-1\}$ the i^{th} SMTF is denoted

$$\boldsymbol{b}^i = b_0^i, b_1^i, \ldots, b_{B_i-1}^i,$$

where $B_i = T_i + 32$ and

$$b_j^i = \begin{cases} s_j, & \text{if } 0 \le j < 32 \\ a_{j-32}^i, & \text{if } 32 \le j < B_i \end{cases}.$$

NOTE – Construction of SMTFs is shown in figure 3-2.

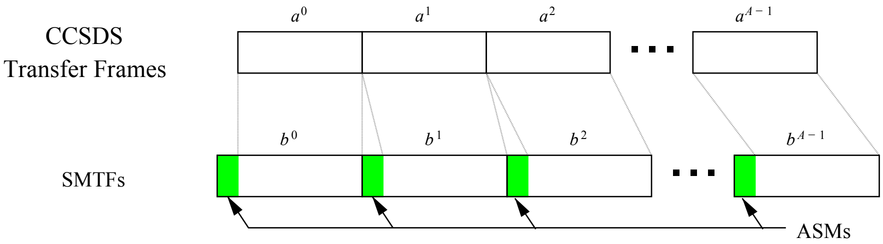

Figure 3-2: ASM Attachment

3.3.2.2 Sequence Specification

The ASM shall be the sequence $\boldsymbol{s} = s_0, s_1, \ldots, s_{31}$, represented in hexadecimal notation as

$$\boldsymbol{s} = \text{1ACFFC1D}.$$

3.3.3 GENERIC FRAME PROCEDURE

3.3.3.1 General

When Generic Frame Procedure (GFP) is used, SMTFs shall be formed using the short GFP mode or the full GFP mode defined in this subsection.

For $i \in \{0,\ 1,\ \dots,\ A-1\}$, the i^{th} SMTF is denoted

$$\boldsymbol{b}^i = b_0^i, b_1^i, \dots,\ b_{B_i-1}^i,$$

where B_i is number of bits in the i^{th} SMTF.

3.3.3.2 Short GFP Mode

When the short GFP mode is used, SMTFs shall be formed by preceding each transfer frame with the core header as defined in section 6.1.1 of reference [6], where the term 'payload area' in reference [6] is understood to refer to the transfer frame.

NOTE – The short GFP mode has the same overhead as the ASM approach defined in 3.3.2.

3.3.3.3 Full GFP Mode

3.3.3.3.1 General

When the full GFP mode is used, each SMTF shall be the GFP client data frame that results from designating a transfer frame as the GFP payload information field and applying the frame-mapped GFP encapsulation methods defined in sections 6 and 7 of reference [6].

NOTES

1 The full GFP mode may be useful for multiplexed trunk lines with fixed or variable length transfer frames with the added overhead present in the payload headers.

2 Reference [6] describes two modes of GFP: frame-mapped (GFP-F) and transparent-mapped (GFP-T). This Experimental Specification utilizes only the GFP-F mode.

3.3.3.3.2 Payload Frame Check Sequence

The payload Frame Check Sequence (pFCS) field of GFP shall not be used.

3.3.3.3.3 User Payload Identifier

When CCSDS frames are used, the user payload identifier within the payload header shall be set to 1111 0000.

NOTE – As provided for by the GFP standard, this setting can be used to indicate data types not enumerated in the GFP standard, such as the CCSDS client data type.

3.3.3.4 GFP Idle Frame

In either the short or full GFP modes, when a transfer frame is not available, an SMTF may be formed using a GFP idle frame, that is, a core header only with no payload area, as defined in section 6.2.1 of reference [6].

NOTE – The use of GFP idle frames will cause more than A SMTFs to exist. For simplicity in the description below, the notation A is still used to refer to the number of SMTFs.

3.3.3.5 Payload Area Scrambling

The payload area scrambling may be disabled. Whether or not the process is applied is a managed parameter.

3.4 SLICER

3.4.1 The sequence of SMTFs shall be zero-padded and sliced into information blocks of length k, as shown in figure 3-3 and described herein.

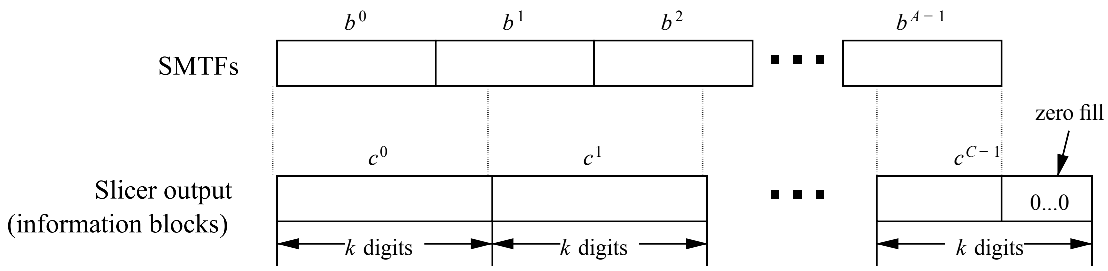

Figure 3-3: Slicer

NOTE – SMTFs can be fixed length (as represented in figure 3-3) or variable length.

3.4.2 The sequence of SMTFs,

$$\boldsymbol{b}^0,\ \boldsymbol{b}^1,\ \dots,\boldsymbol{b}^{A-1},$$

is a vector of vectors that can be viewed as a single vector with binary digits in the same order,

$$\hat{\boldsymbol{b}} = \hat{b}_0, \hat{b}_1,\ \dots,\ \hat{b}_{B-1},$$

where

$$B = \sum_{i=0}^{A-1} B_i.$$

3.4.3 The sequence $\widehat{\boldsymbol{b}}$ shall be padded at its end with the minimum number of zeroes so that its length is a multiple of k. The sequence $\widetilde{\boldsymbol{b}}$ is denoted by

$$\widetilde{\boldsymbol{b}} = \hat{b}_0, \hat{b}_1, \ldots, \hat{b}_{B-1}, \underbrace{0, 0, \ldots, 0}_{P},$$

where

$$\tilde{b}_i = \begin{cases} \hat{b}_i, & \text{if } 0 \le i < B \\ 0, & \text{if } B \le i < B + P \end{cases},$$

and

$$P = \min\{ p : k \mid B + p \}.$$

3.4.4 The slicer shall re-index $\widetilde{\boldsymbol{b}}$ into $C = (B + P)/k$ blocks each of length k:

$$\boldsymbol{c}^0, \boldsymbol{c}^1, \ldots, \boldsymbol{c}^{C-1},$$

where for $i \in \{0, 1, \ldots, C-1\}$, the i^{th} block is denoted $\boldsymbol{c}^i = c_0^i, c_1^i, \ldots, c_{k-1}^i$, and for $j \in \{0, 1, \ldots, k-1\}$, the j^{th} symbol of the i^{th} block is

$$c_j^i = \tilde{b}_{ki+j}.$$

NOTE – Information block sizes for RS-PC coding are defined in table 3-1.

Table 3-1: Information Block Sizes for RS-PC Coding

Length of information block for RS-PC Coding in bytes k_{RSPC}
$k_I k_O M$

NOTE – $k_I = 204$, $k_O = 223$, and M indicates the number of concatenated blocks.

3.5 FORWARD ERROR CORRECTION FOR OUTER PARITY

3.5.1 OVERVIEW

The structure of the Forward Error Correction (FEC) block is discussed in this and subsequent subsections. Figure 3-4 illustrates the composition of the block format. The information block, sub-data, and Outer Parity (PO) are discussed in this subsection; the interleaver is discussed in 3.6; the Inner Parity (PI) is discussed in 3.7; and the synchronization method is discussed in 3.9.

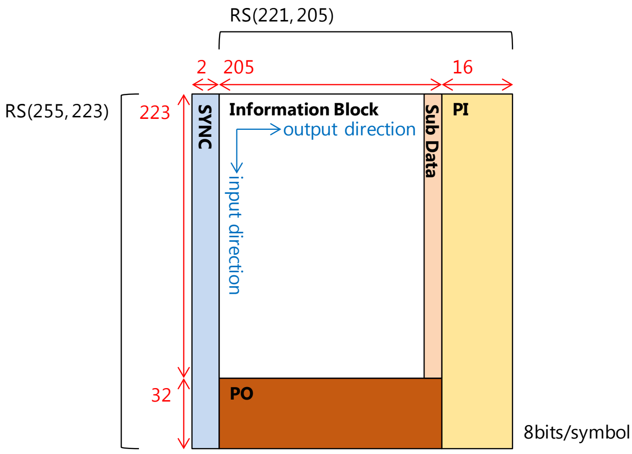

Figure 3-4: Forward Error Correction Block Format

3.5.2 REQUIREMENTS

3.5.2.1 An FEC code shall be applied to the FEC input frames, $\boldsymbol{c}^i = c_0^i, c_1^i, \dots, c_k^i$, to produce FEC output frames, $\boldsymbol{q} = \boldsymbol{q}^0, \boldsymbol{q}^1, \dots, \boldsymbol{q}^{C'-1}$, with $\boldsymbol{q}^i = q_0^i, q_1^i, \dots, q_{2040}^i$ as described herein.

3.5.2.2 The input to the encoder shall be information blocks of size $k_{RSPC} = k_I k_O M$ bytes and corresponding sub-data of size $k_O M$ bytes.

3.5.2.3 The sequence of SMTFs shall be sliced into information blocks of length k_O bytes. Each information block of size k_O bytes shall be encoded by the RS encoder.

3.5.2.4 For each $k_I k_O$ byte information block, k_O bytes of sub-data shall be inserted. The contents are implementation-specific and can be used for in-band signaling. The sub-data shall also be encoded by the Reed-Solomon (RS) encoder.

3.5.2.5 The RS code (see reference [7]) shall have the following parameters: $J = 8,\ E = 16$.

3.5.2.6 The output of the RS(255,223) encoder is a codeword of 255 bytes = 2040 bits.

3.5.2.7 The produced frames $\boldsymbol{q}$ can be denoted as shown below. In this expression, $\boldsymbol{c}^i$ is i^{th} input frame, $\boldsymbol{p}_O^i$ is the RS parity corresponding to the frame, $\boldsymbol{c}_s^j$ is j^{th} sub-data, and $\boldsymbol{p}_s^j$ is the RS parity corresponding to the sub-data.

$$\boldsymbol{q}^{(k_I+1)j+i} = \begin{cases} \boldsymbol{c}^{k_I j+i},\ \boldsymbol{p}_O^{k_I j+i}, & \text{if } 0 \leq i < k_I - 1, \\ \boldsymbol{c}_s^j,\ \boldsymbol{p}_s^j, & \text{if } i = k_I. \end{cases}$$

3.5.2.8 $C' = (k_I + 1)C/k_I$ is the number of RS codewords including the codeword of sub-data.

3.6 CHANNEL INTERLEAVER

3.6.1 ROW/COLUMN BINARY BLOCK INTERLEAVER

3.6.1.1 General

For Optical On-Off-Keying (O3K), the sequence of FEC output frames $\boldsymbol{q} = \boldsymbol{q}^0, \boldsymbol{q}^1, \ldots, \boldsymbol{q}^{C'-1}$ shall be channel-interleaved with a block interleaver as shown in figure 3-5 and described herein.

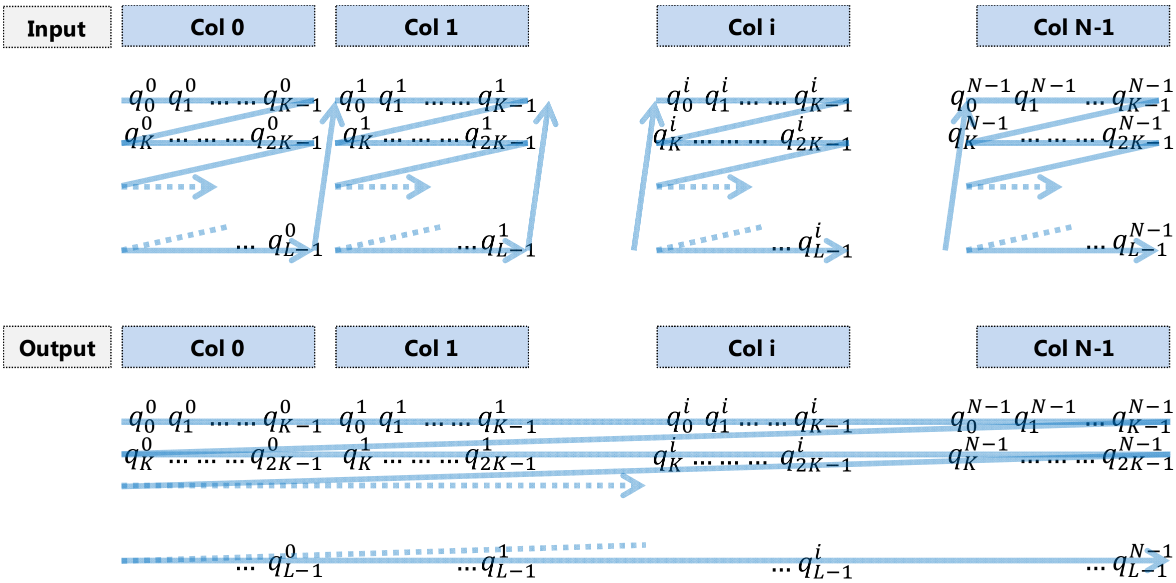

Figure 3-5: Block Channel Interleaver

NOTE – The interleaver is parameterized with three parameters: K, the number of binary digits per interleaver symbol; N, the number of columns in the channel interleaver; and L, the number of rows in the interleaver.

- The number of binary digits in a column, L, is set equal to 2040, which corresponds to the number of binary digits in an FEC output frame.
- The number of binary digits per interleaver symbol, K, is set to 8, which corresponds to the number of binary digits in an RS symbol.

– The number of columns in the channel interleaver, N, is set equal to $N = (k_I + 1)M$. The number of concatenated blocks, M, is a managed parameter.

3.6.1.2 Channel Interleaver Input Notation

The sequence of minor FEC frames, $\boldsymbol{q} = \boldsymbol{q}^0, \boldsymbol{q}^1, \ldots, \boldsymbol{q}^{C'-1}$, is a vector of vectors that can be viewed as a single vector of interleaver binary digits,

$$\widehat{\boldsymbol{q}} = \hat{q}_0, \hat{q}_1, \ldots, \hat{q}_{L\times C'-1},$$

where for $i \in \{0, 1, \ldots, C'-1\}$ and $j \in \{0, 1, \ldots, L-1\}$,

$$\hat{q}_{L\times i+j} = q_j^i.$$

3.6.1.3 Channel Interleaver Operation

3.6.1.3.1 General

The input interleaver binary digits, $\widehat{\boldsymbol{q}}$, shall be serially written into the interleaver column-wise, and then the interleaver symbols of K binary digits shall be serially read out row-wise.

NOTE – The correspondence between r_j^i, the j^{th} bit of the i^{th} interleaver output frame, and q_k^l, the k^{th} bit of the l^{th} interleaver input frame, is:

$$r_j^i = q_k^l \; with \; i = \left\lfloor \frac{l}{N} \right\rfloor, \; and \; j = \left\lfloor \frac{k}{K} \right\rfloor K\,N + K(l - \left\lfloor \frac{l}{N} \right\rfloor N) + (k\%K),$$

where $\lfloor x \rfloor$ denotes the integer part of x and $k\%K$ denotes the remainder of k divided by K.

3.6.1.3.2 Re-Indexing Channel Interleaver Output to Form Interleaved Codewords

The sequence $\boldsymbol{r}$ may be re-indexed into $R = C'/N$ blocks, each containing $L \times N$ binary digits:

$$\boldsymbol{r} = \boldsymbol{r}^0, \boldsymbol{r}^1, \ldots, \boldsymbol{r}^{R-1},$$

where for $i \in \{0, 1, \ldots, R-1\}$, the i^{th} block is denoted $\boldsymbol{r}^i = r_0^i, r_1^i, \ldots, r_{L\times N-1}^i$, and for $j \in \{0, 1, \ldots, L\times N-1\}$,

$$\hat{r}_{L\times Ni+j} = r_j^i.$$

NOTE – Each $\boldsymbol{r}^i$ is called a raw interleaved block.

3.7 FORWARD ERROR CORRECTION FOR INNER PARITY

3.7.1 GENERAL

A FEC code shall be applied again to the raw interleaved block, $\boldsymbol{r} = \boldsymbol{r}^0,\ \boldsymbol{r}^1,\ \dots,\ \boldsymbol{r}^{R-1}$, to produce FEC output frames, $\boldsymbol{s} = \boldsymbol{s}^0, \boldsymbol{s}^1,\ \dots,\ \boldsymbol{s}^{R-1}$, as described herein.

3.7.2 OPERATION

3.7.2.1 The input to the encoder shall be interleaved blocks of size $(k_I + 1)LM/8$ bytes.

3.7.2.2 The sequence of interleaved blocks shall be sliced into information blocks of length $k_I + 1$ bytes. Each information block of size $k_I + 1$ bytes shall be encoded by the RS encoder.

3.7.2.3 The RS code shall have the parameters $J = 8$ and $E = 8$ and shall be shortened to RS(221,205) by ignoring 34 symbols of RS(255,239).

NOTE – The output of the RS(221,205) encoder is a codeword of 221 bytes = 1768 bits.

3.7.2.4 For $j \in \{0, 1, \dots, ML/8 - 1\}$, the produced frames, $\boldsymbol{s}$, may be denoted as follows:

$$\boldsymbol{s}^i = \boldsymbol{s}[0]^i, \boldsymbol{s}[1]^i,\ \dots,\ \boldsymbol{s}[ML/8 - 1]^i$$

$$\boldsymbol{s}[j]^i = \boldsymbol{r}[j]^i,\ \boldsymbol{p}_I[j]^i$$

NOTE – In this expression, $\boldsymbol{r}[j]^i$ is j^{th} input frame in i^{th} interleaved block:

$$\boldsymbol{r}[j]^i = r^i_{(k_I+1)j},\ r^i_{(k_I+1)j+1},\ \dots,\ r^i_{(k_I+1)(j+1)-1}.$$

The $\boldsymbol{p}_I[j]^i$ is the RS parity corresponding to the frame $\boldsymbol{r}[j]^i$, and each $\boldsymbol{s}^i$ is called an interleaved block.

3.8 PSEUDO-RANDOMIZER (OPTIONAL)

3.8.1 GENERAL

3.8.1.1 Each interleaved block may be pseudo-randomized by performing the digit-wise modulo-2 addition with a pseudo-random sequence as shown in figure 3-6 and described herein. Whether or not this procedure is applied is optional and shall be determined by a managed parameter.

3.8.1.2 For $i \in \{0, 1, \dots, R - 1\}$, the i^{th} pseudo-randomized interleaved block may be denoted $\boldsymbol{t}^i = t^i_0,\ t^i_1, \dots,\ t^i_{LN-1}$, where for $j \in \{0,1, \dots, LN - 1\}$, the j^{th} symbol of the i^{th} block is

$$t^i_j = s^i_j \oplus p_j,$$

where $\oplus$ represents modulo-2 addition.

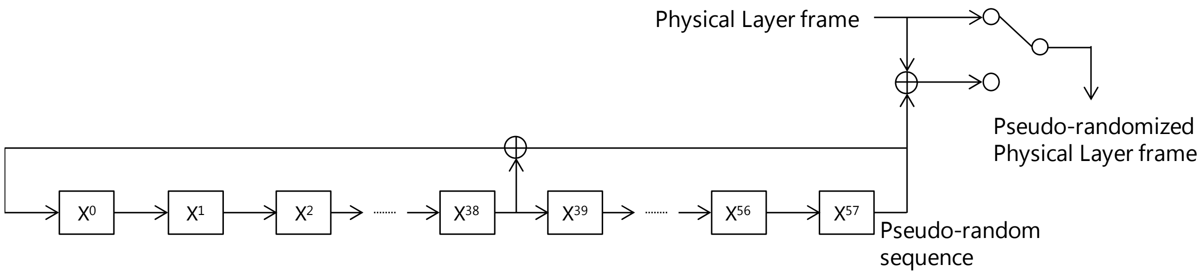

Figure 3-6: Pseudo-Randomizer Implementation Example

3.8.1.3 For $j \in \{0, 1, \dots, ML/8 - 1\}$, the produced frames, $\boldsymbol{t}$, may be denoted as shown below:

$$\boldsymbol{t}^i = \boldsymbol{t}[0]^i,\ \boldsymbol{t}[1]^i,\ \dots,\ \boldsymbol{t}[ML/8-1]^i$$

$$\boldsymbol{t}[j]^i = t^i_{1768j},\ t^i_{1768j+1},\ \dots,\ t^i_{1768(j+1)-1}$$

3.8.2 SEQUENCE SPECIFICATION

The pseudo-random sequence $p_0, p_1, \dots, p_{LN-1}$ shall be generated by the polynomial:

$$g(D) = D^{58} + D^{39} + 1.$$

3.8.3 SEQUENCE INITIALIZATION

This pseudo-random sequence shall begin at the first digit of the codeword with the inner parity. The registers in the sequence generator shall be initialized to 0x200E55A47F5B774 at the start of the codeword.

3.9 PHYSICAL LAYER FRAMING

3.9.1 A Physical Layer Synchronization Marker (PLSM) consisting of $2LM$ binary digits shall be prepended to each interleaved block to create a Physical Layer frame.

3.9.2 For $j \in \{0, 1, \dots, ML/8 - 1\}$, the produced frames $\boldsymbol{u}$ may be denoted as shown below.

$$\boldsymbol{u}^i = \boldsymbol{u}[0]^i,\ \boldsymbol{u}[1]^i,\ \dots,\ \boldsymbol{u}[ML/8-1]^i$$

$$\boldsymbol{u}[j]^i = u[j]^i_0, u[j]^i_1, \dots, u[j]^i_{1783}$$

$$u[j]^i_k = \begin{cases} w[j]_k, & \text{if } 0 \le k < 16 \\ t[j]^i_{k-16}, & \text{if } 16 \le k < 1783 \end{cases}$$

NOTE – The contents of PLSM $w[j]_k$ are implementation-specific and can be used to determine the boundary of an RS codeword and an interleaved block.

3.9.3 If the 8b/10b encoding is used, the control codes may be used for PLSM as described in 3.10. Otherwise, the sequence of Physical Layer frames shall be $\boldsymbol{u} = \boldsymbol{u}^0, \boldsymbol{u}^1, \ldots, \boldsymbol{u}^{R-1}$.

3.10 8B/10B ENCODING (OPTIONAL)

3.10.1 The Physical Layer frames may be encoded with 8b/10b before transmitting the data to keep DC-balance and bounded disparity. Whether or not 8b/10b is used is specified by a managed parameter.

3.10.2 For $j \in \{0, 1, \ldots, ML/8 - 1\}$, the produced frames $\boldsymbol{v}$ may be denoted as shown below.

$$\boldsymbol{v}^i = \boldsymbol{v}[0]^i,\ \boldsymbol{v}[1]^i,\ \ldots,\ \boldsymbol{v}[ML/8 - 1]^i$$

$$\boldsymbol{v}[j]^i = v[j]_0^i, v[j]_1^i, \ldots, v[j]_{2229}^i$$

$$v[j]_k^i = \begin{cases} w'[j]_k, & \text{if } 0 \le k < 20 \\ t'[j]_{k-20}^i, & \text{if } 20 \le k < 2229 \end{cases}$$

NOTE – In this expression, 10-bit symbols of 8b/10b are used as PLSM $w'[j]_k$ and the contents of PLSM are implementation-specific. The $\boldsymbol{t}'$ is the 8b/10b encoded sequence of $\boldsymbol{t}$.

3.10.3 If the 8b/10b encoding is used, the sequence of Physical Layer frames shall be $\boldsymbol{v} = \boldsymbol{v}^0, \boldsymbol{v}^1, \ldots, \boldsymbol{v}^{R-1}$.

4 MANAGED PARAMETERS

4.1 OVERVIEW

Some parameters for optical signaling are handled by management rather than by an inline communications protocol. The managed parameters are those that tend to be static for long periods of time, and whose change generally signifies a major reconfiguration of the high data rate signaling associated with a particular mission. A management system conveys the required information to the high data rate optical signaling systems.

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

4.2 MANAGED PARAMETERS FOR CODING AND SYNCHRONIZATION

The managed parameters for coding and synchronization shall be those specified in table 4-1.

Table 4-1: Managed Parameters for Coding and Synchronization

Managed Parameter	Allowed Values
SMTF generation method	ASM or GFP
GFP mode	Short or full
GFP payload area scramble	Enable or disable
The number of concatenated blocks	Positive integer
Pseudo-randomizer	Enable or disable
8b/10b encoding	Enable or disable

ANNEX A

ACRONYMS AND ABBREVIATIONS

(INFORMATIVE)

AOS	Advanced Orbiting Systems
ASM	attached synchronization marker
AWGN	additive white Gaussian noise
DSP	digital signal processor
DVB	digital video broadcasting
FEC	forward error correction
GFP	generic frame procedure
GFP-F	generic frame procedure frame-mapped
GFP-T	generic frame procedure transparent-mapped
HDLC	high-level data link control
IP/PPP	Internet Protocol/Point-to-Point Protocol
LEO	low Earth orbit
MSB	most significant bit
O3K	optical on-off-keying
OSI	Open Systems Interconnection
pFCS	payload frame check sequence
PLFM	Physical Layer frame marker
PI	inner parity
PPP	point-to-point protocol
PO	outer parity
RS	Reed-Solomon
RS-PC	Reed-Solomon product code
SMTF	synchronization-marked transfer frame
TM	telemetry
USLP	Unified Space Data Link Protocol

ANNEX B

SIMULATION RESULTS OF RS-PC AS IMPLEMENTATION

(INFORMATIVE)

OVERVIEW

To establish the performance of the RS-PC and show the effect of a block channel interleaver over a fading channel, a bit error rate simulation over Additive White Gaussian Noise (AWGN) employing a fading channel was run as shown in reference [C2].

The simulator incorporates the fading vector D from reference [C3] to evaluate the effectiveness of the error correction proposed in this book at different block lengths. Advantages of the block interleaver proposed in this book compared to a convolutional interleaver are also shown.

SIMULATION TOOL

The simulator used for the results is Matlab/Simulink R2020a with the following toolboxes:

– Communications Toolbox;

– Digital Signal Processor (DSP) System Toolbox;

– Signal Processing Toolbox.

ATMOSPHERIC CHANNEL

A fading channel model of reference [C3] was applied in the calculation in reference [C3] to show the effect of the block channel interleaver.

ANNEX C

INFORMATIVE REFERENCES

(INFORMATIVE)

[C1] *IEEE Standard for Ethernet*. IEEE Std 802.3-2022. Piscataway, New Jersey: IEEE, 2022.

[C2] Hiroaki Yamazoe, et al. “Evaluation of the Forward Error Correction Format for LEO-Ground Optical Communication Using Reed-Solomon Product Code.” In *Proceedings of SPIE 11678, Free-Space Laser Communications XXXIII (6–11 March 2021, Online Only)*. Edited by Hamid Hemmati and Don M. Boroson. Proceedings Volume 11678. Bellingham, Washington: SPIE, 2021.

[C3] Dirk Giggenbach, et al. “Reference Power Vectors for the Optical LEO Downlink Channel.” In *Proceedings of 2019 IEEE International Conference on Space Optical Systems and Applications (ICSOS 2019) (14–16 October 2019, Portland, Oregon)*. Piscataway, New Jersey: IEEE Conference Publications, 2019.