The Consultative Committee for Space Data Systems

Draft Recommendation for Space Data System Standards

NON-COHERENT OPTICAL COMMUNICATIONS CODING AND SYNCHRONIZATION

DRAFT RECOMMENDED STANDARD

CCSDS 142.0-P-1.1

PINK SHEETS

November 2023

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DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 142.0-B-1	Optical Communications Coding and Synchronization, Recommended Standard, Issue 1	August 2019	Original issue
CCSDS 142.0-P-1.1	Non-Coherent Optical Communications Coding and Synchronization, Draft Recommended Standard, Issue 1.1	November 2023	Current draft

NOTE – Sections 4 and 6 and annexes C and D are new in their entirety and are presented without markup to improve readability.

1 INTRODUCTION

1.1 PURPOSE

The purpose of this Recommended Standard is to specify the channel coding and synchronization schemes for free space optical communications systems used by space missions.

The primary applications addressed in this issue of the Recommended Standard ~~is~~are space-to-ground and ground-to-space links through an atmospheric channel in a photon-starved regime and a high photon flux regime; use of the Recommended Standard for other applications or operating conditions is not precluded.

In photon-starved links, the photon-efficiency of the link is of primary concern. When provided with a set of CCSDS transfer frames produced by the Data Link Protocol Sublayer (as specified in reference [1], [2], or [8]), this specification allows one to determine the binary vector to be provided to the Physical Layer. The 'ones' and 'zeroes' of the binary vector indicate the slots that are to be pulsed and non-pulsed, respectively, in the optical transmission. The physical characteristics of such transmissions are addressed in *Optical Communications Physical Layer* (reference [3]).

In high photon flux links, the number of photons per second is in the order of 10^{10} and is not a concern, and a pulsed modulation is not required.

1.2 SCOPE

This Recommended Standard defines Coding and Synchronization Sublayer schemes in terms of the signal characteristics and procedures involved in the encoding and synchronization of the 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.

This Issue ~~1~~ includes a specification for High Photon Efficiency (HPE) systems, in which the photon-efficiency of the link is of primary concern~~.[1]~~, and a specification for Optical On-Off Keying (O3K) systems, which is designed for high photon flux links.

~~[1] A subsequent issue of this Recommended Standard may provide a specification for low-complexity and/or high-data-rate optical communications.~~

1.5 DOCUMENT STRUCTURE

This document is divided into five numbered sections and five annexes:

a) section 1 presents the purpose, scope, applicability, rationale, document structure, definitions, 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 ~~HPE~~ telemetry signaling for HPE;

d) section 4 specifies telemetry signaling for O3K;

e) section 5 specifies HPE beacon and optional Advanced Orbiting Systems (AOS) transfer frame signaling;

f) section 6 specifies optical ranging techniques;

g) section 7 lists the managed parameters;

h) annex A is the Protocol Implementation Conformance Statement (PICS) proforma;

i) annex B defines the service provided to the users;

j) annex C provides exponent matrix tables for LDPC Codes;

k) annex D specifies the generation of Gold sequences;

l) annex E discusses security, SANA, and patent considerations;

m) annex F lists abbreviations and terms used within this document;

n) annex G provides a list of informative references.

1.6 DEFINITIONS

1.6.1 DEFINITIONS FROM THE OPEN SYSTEM INTERCONNECTION BASIC REFERENCE MODEL

This Recommended Standard makes use of a number of terms defined in reference [4]. The use of those terms in this Recommended Standard is to be understood in a generic sense, that is, 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; and

d) service data unit.

1.9 REFERENCES

The following publications 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 documents.

[1] *TM Space Data Link Protocol*. Issue ~~2~~3. Recommendation for Space Data System Standards (Blue Book), CCSDS 132.0-B-~~2~~3. Washington, D.C.: CCSDS, ~~September 2015~~October 2021.

[2] *AOS Space Data Link Protocol*. Issue ~~3~~4. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.0-B-~~3~~4. Washington, D.C.: CCSDS, ~~September 2015~~October 2021.

[3] *Optical Communications Physical Layer*. Issue ~~1~~2. Recommendation for Space Data System Standards (Blue Book), CCSDS 141.0-B-~~1~~2. ~~Washington, D.C.: CCSDS, August 2019~~Forthcoming.

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

[6] *TC Synchronization and Channel Coding*. Issue ~~3~~4. Recommendation for Space Data System Standards (Blue Book), CCSDS 231.0-B-~~3~~4. Washington, D.C.: CCSDS, ~~September 2017~~July 2021.

[7] *TM Synchronization and Channel Coding*. Issue ~~3~~4. Recommendation for Space Data System Standards (Blue Book), CCSDS 131.0-B-~~3~~4. Washington, D.C.: CCSDS, ~~September 2017~~April 2022.

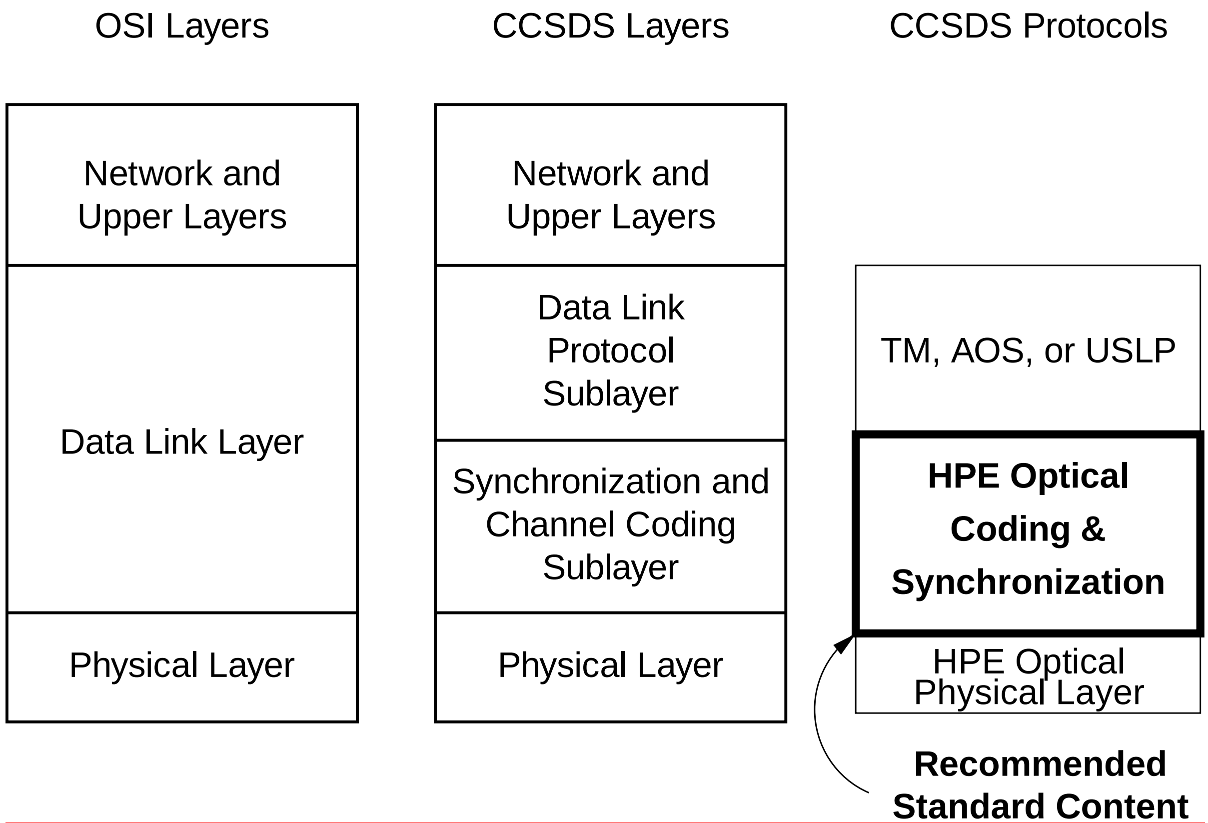
[8] *Unified Space Data Link Protocol*. Issue ~~1~~2. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.1-B-~~1~~2. Washington, D.C.: CCSDS, October ~~2018~~2021.

[9] *Data Transmission and PN Ranging for 2 GHz CDMA Link via Data Relay Satellite*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 415.1-B-1. Washington, D.C.: CCSDS, September 2011.

2 OVERVIEW

2.1 ARCHITECTURE

Figure 2-1 illustrates the relationship of this Recommended Standard to the Open System 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; possible Space Data Link Protocols using optical communications are the Telemetry (TM) Space Data Link Protocol (reference [1]), the AOS Space Data Link Protocol (reference [2]), and the Unified Space Data Link Protocol (USLP) (reference [8]). The Optical Communications Coding and Synchronization Protocol specified in this Recommended Standard provides the functions of the Synchronization and Channel Coding Sublayer of the Data Link Layer for transferring transfer frames over an optical space link.



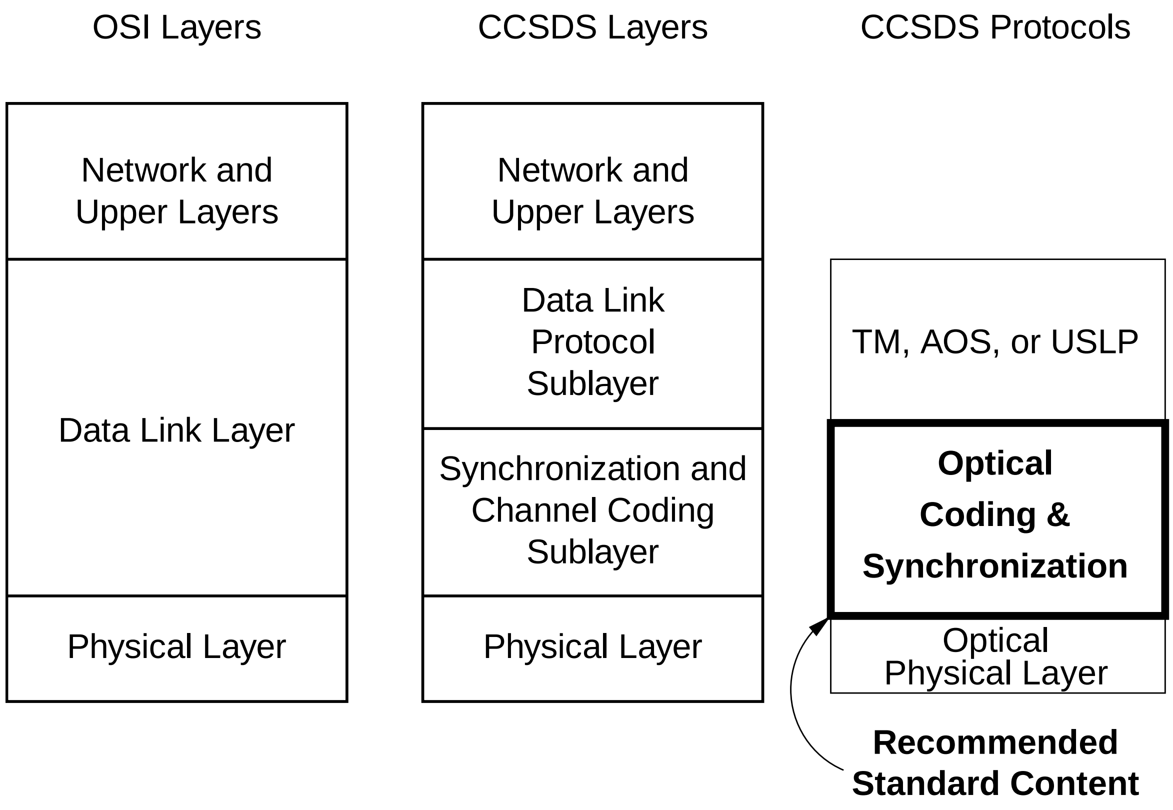


Figure 2-1: Relationship with OSI Layers

2.2 SUMMARY OF FUNCTIONS

The optical Coding and Synchronization Sublayer provides the following functions for transferring transfer frames over an optical space link:

a) channel coding;

b) synchronization; and

c) telemetry transfer frame validation.

This Recommended Standard includes a specification for the transmission of telemetry transfer frames, AOS transfer frames, or fixed-length USLP transfer frames, and a separate specification for beacon and optional transmission of AOS transfer frames or fixed-length USLP transfer frames. In a typical implementation, telemetry signaling would occur from space to ground (downlink), and beacon and optional AOS/USLP transfer frame signaling would occur from ground to space (uplink), but this Recommended Standard does not prescribe the link direction or geometry. These transmissions occur simultaneously and continuously at opposite ends of the link during each communications session.

The telemetry link specification defines the relationship between input CCSDS transfer frames and output ~~pulsed slots. For the HPE application, this specification~~signal. This includes the following functions: CCSDS transfer frame ~~slicer~~adaptation, CRC, channel coding including frame validation, modulation, channel ~~interleaver~~interleaving, codeword synchronization ~~marker, repeat~~marking, repetition, pseudo-randomization, sync-layer framing including sync layer signaling, slot ~~mapper~~mapping, and guard slot insertion. Some functions only apply to the HPE regime, and others only to the O3K regime.

The beacon specification, applicable only to the HPE regime, includes optional transmission of AOS/USLP transfer frames. The specification defines the relationship between sending-end input frames (from upper layer) and output pulsed slots (to lower layer). The specification includes functions to: 1) provide a reference beacon, 2) aid synchronization, and 3) support an AOS/USLP transfer frame transmission capability.

The overall architecture of the optical communications system is shown in figure 2-2. Throughout the communications session, the optical Terminal A ~~transmits~~may optionally transmit a beacon, ~~together with optional AOS/USLP transfer frame data. The~~in which case the Terminal B receiver locks onto the beacon and uses it to assist in accurately pointing its optical transmitter. ~~Any~~In the case of HPE, the beacon may be accompanied by optional AOS/USLP transfer frame data, which is ~~also~~ decoded onboard. O3K allows no data to accompany the beacon. Telemetry is transmitted from Terminal B and received by Terminal A.

This Recommended Standard specifies the coding and synchronization features of the Terminal A and Terminal B transmitters, and a few details of the functions required at the receivers, including frame validation. In a typical application, Terminal A on the ground transmits an uplink beacon and optional AOS/USLP transfer frame data to Terminal B in space, and Terminal B transmits a downlink telemetry signal to Terminal A.

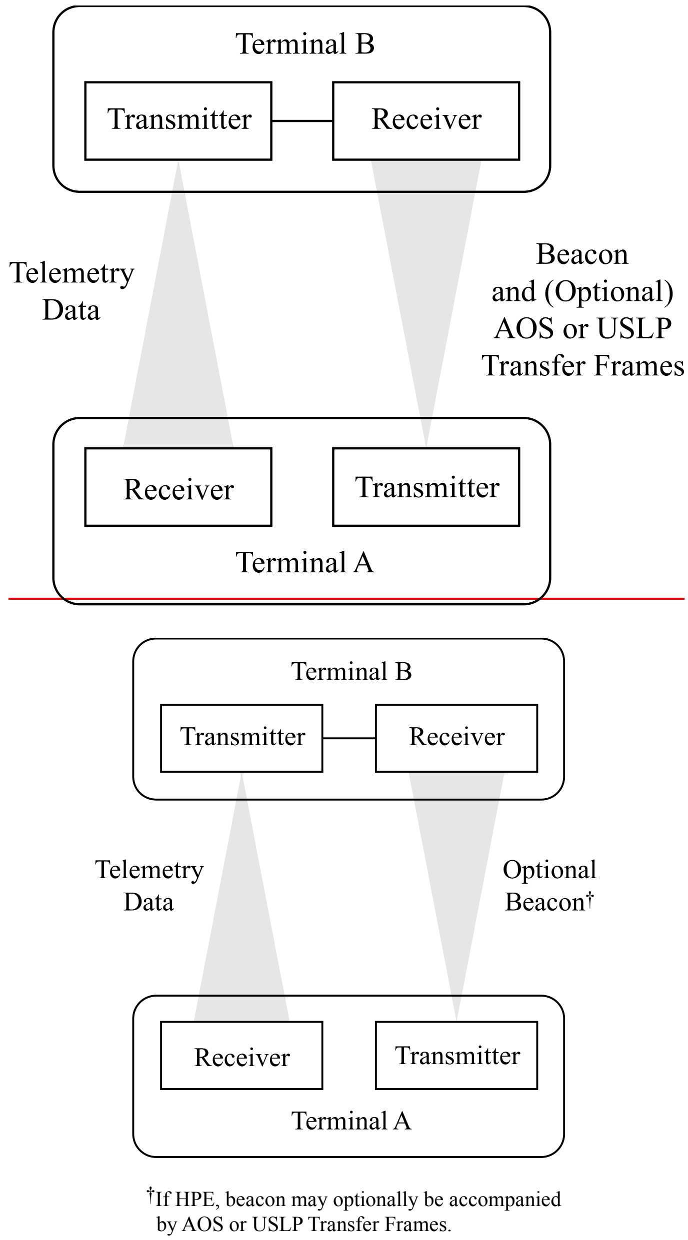


Figure 2-2: Overall Architecture of the Optical Communications System

2.3 INTERNAL ORGANIZATION OF TELEMETRY SIGNALING AT THE CODING AND SYNCHRONIZATION SUBLAYER

2.3.1 TELEMETRY SIGNALING AT THE SENDING END

Figure 2-3 shows the internal organization of the Coding and Synchronization Sublayer of telemetry signaling at 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.

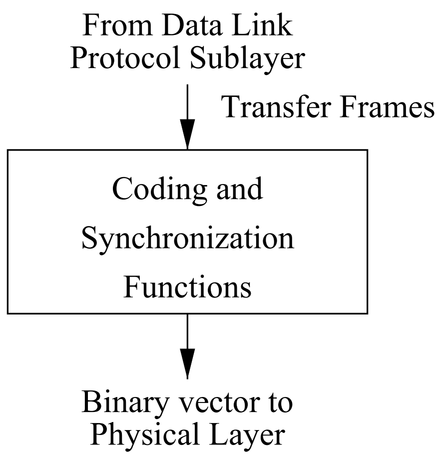


Figure 2-3: Internal Organization of Telemetry Signaling at the Sending End

At the sending end, the Coding and Synchronization Sublayer accepts transfer frames of fixed length and constant rate from the Data Link Protocol Sublayer (see figure 2-1), performs functions selected for the mission, and delivers a binary vector to the Physical Layer~~ to indicate which slots~~. For HPE, which uses Pulse-Position Modulation (PPM), the binary vector indicates which slots are to contain light pulses. For O3K, the binary vector indicates which On-Off Keying (OOK) symbols are to contain light pulses.

2.3.2 TELEMETRY SIGNALING AT THE RECEIVING END

2.3.2.1 General

Figure 2-4 shows the internal organization of the Coding and Synchronization Sublayer for telemetry signaling at 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. Organization of CCSDS optical communications sublayering differs from that of the CCSDS protocol specifications for Radio Frequency (RF) communications in that the demodulation function is specified at the Coding and Synchronization Sublayer (this document) rather than at the Physical Layer (reference [3]).

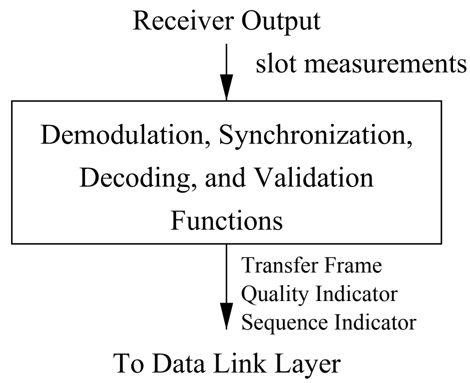


Figure 2-4: Internal Organization of Telemetry Signaling at the Receiving End

~~A~~For HPE, at the receiving end, the Coding and Synchronization Sublayer accepts receiver outputs from the Physical Layer and performs functions selected for the mission. The receiver outputs are slot measurements, which are receiver estimates of the intensity of light, number of photons observed, or related statistic, for each slot of the received transmission. Among these functions is codeword synchronization and Serially Concatenated convolutionally coded Pulse Position Modulation (SCPPM) decoding, from which Synchronization-Marked Transfer Frames (SMTFs) are recovered. Synchronization Markers present in the SMTF allow synchronization and recovery of each transfer frame, which is delivered to the Data Link Protocol Sublayer along with a quality indicator and sequence indication.

For O3K, at the receiving end, the Coding and Synchronization Sublayer accepts receiver outputs from the Physical Layer and performs functions selected for the mission. Among these functions is frame synchronization and Forward Error Correction decoding, from which SMTFs are recovered if frame adaptation was performed. Synchronization markers present in the SMTF allow synchronization and recovery of each transfer frame, which is delivered to the Data Link Protocol Sublayer along with a quality indicator and sequence indication.

2.3.2.2 Telemetry Transfer Frame Validation

After ~~SCPPM~~ decoding and transfer frame recovery is performed, the upper layers at the receiving end also need to know whether or not each recovered transfer frame can be used as a valid data unit; that is, an indication of the quality of the received frame is needed. This function is called transfer frame validation and produces the quality indicator.

The ~~SCPPM~~ decoder can determine, with a very high probability, whether or not each ~~SCPPM~~ codeword ~~can be~~was correctly decoded. Any transfer frames that are recovered from only correctly decoded ~~SCPPM~~ codewords are marked valid; transfer frames recovered from one or more incorrectly decoded codewords are marked invalid.

NOTE – The Frame Error Control Field defined in reference [1], [2], or [8] may also be used for additional frame validation in the Data Link Protocol Sublayer.

2.3.2.3 Synchronization

This Recommended Standard specifies a method for synchronizing telemetry transfer frames using an Attached Synchronization Marker (ASM) (see 4.3.3).

2.4 INTERNAL ORGANIZATION OF BEACON AND AOS/USLP TRANSFER FRAME SIGNALING AT THE CODING AND SYNCHRONIZATION SUBLAYER

2.4.1 INTRODUCTION

This subsection applies only to HPE, as the beacon is not modulated with data for O3K.

2.4.2 AOS/USLP TRANSFER FRAME SIGNALING AT THE SENDING END

Figure 2-5 shows the internal organization of AOS/USLP transfer frame signaling at the Coding and Synchronization 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.

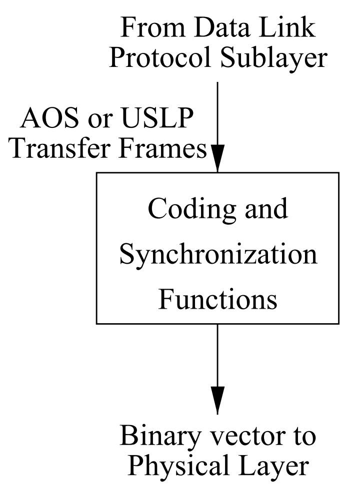


Figure 2-5: Internal Organization of AOS/USLP Transfer Frame Signaling at the Sending End

At the sending end, the Coding and Synchronization Sublayer accepts AOS or USLP fixed-length transfer frames from the Data Link Protocol Sublayer (see figure 2-5). It then performs functions selected for the mission and generates Low-Density Parity-Check (LDPC) encoded Synchronization-Marked Codewords (SMCWs). These SMCWs are Pseudo-random Noise (PN)-spread and mapped into ~~2-~~Binary Pulse Position Modulation (2-PPM) symbols. Two guard slots are inserted to the 2-PPM symbol stream and sent to the Physical Layer.

4 O3K TELEMETRY SIGNALING

4.1 OVERVIEW

This Recommended Standard operates by taking CCSDS TM, AOS, or USLP transfer frames as input and producing a binary vector as output to the Physical Layer. The binary vector indicates which OOK symbols are to contain light pulses.

No intervening slots (data or fill) are added to this output. The functional blocks of the architecture at the sending end are shown in figure 4-1, along with the notation used in the following subsections that defines these functions mathematically. It should be understood that the functions need not be implemented explicitly as defined here; any implementation producing the proper binary vector complies with the standard.

As shown in figure 4-1, optional transfer frames adaptation is performed (4.3). An ASM is prepended to each transfer frame, forming an SMTF. The stream of SMTFs is sliced into information blocks (4.3.4) which are provided as input to the channel encoder (4.4).

Two different encoders are described, a Reed-Solomon (RS) (255,223) code (4.4.2) and rate 1/2 and 9/10 LDPC codes (4.4.3). Codewords are then channel interleaved (4.5), optionally repeated (4.6), and randomized (4.7).

The sync layer framing is performed (4.8): the SLFRAME header, composed of a sync marker and additional signaling fields (in-band signaling, interleaver signaling), is prepended to each major code frame. Each OOK symbol is then optionally repeated (4.9). The variation of the symbol rate provides another scheme to perform variation of the data rate.

At the receiving end, two levels of synchronization are required: SLFRAME synchronization (identified by the SLFRAME header sync marker) and transfer frame synchronization (identified by the ASM). SLFRAME synchronization is achieved by recognizing the specific symbol pattern of the header sync marker in the symbol stream. This synchronization is then verified by making further checks.

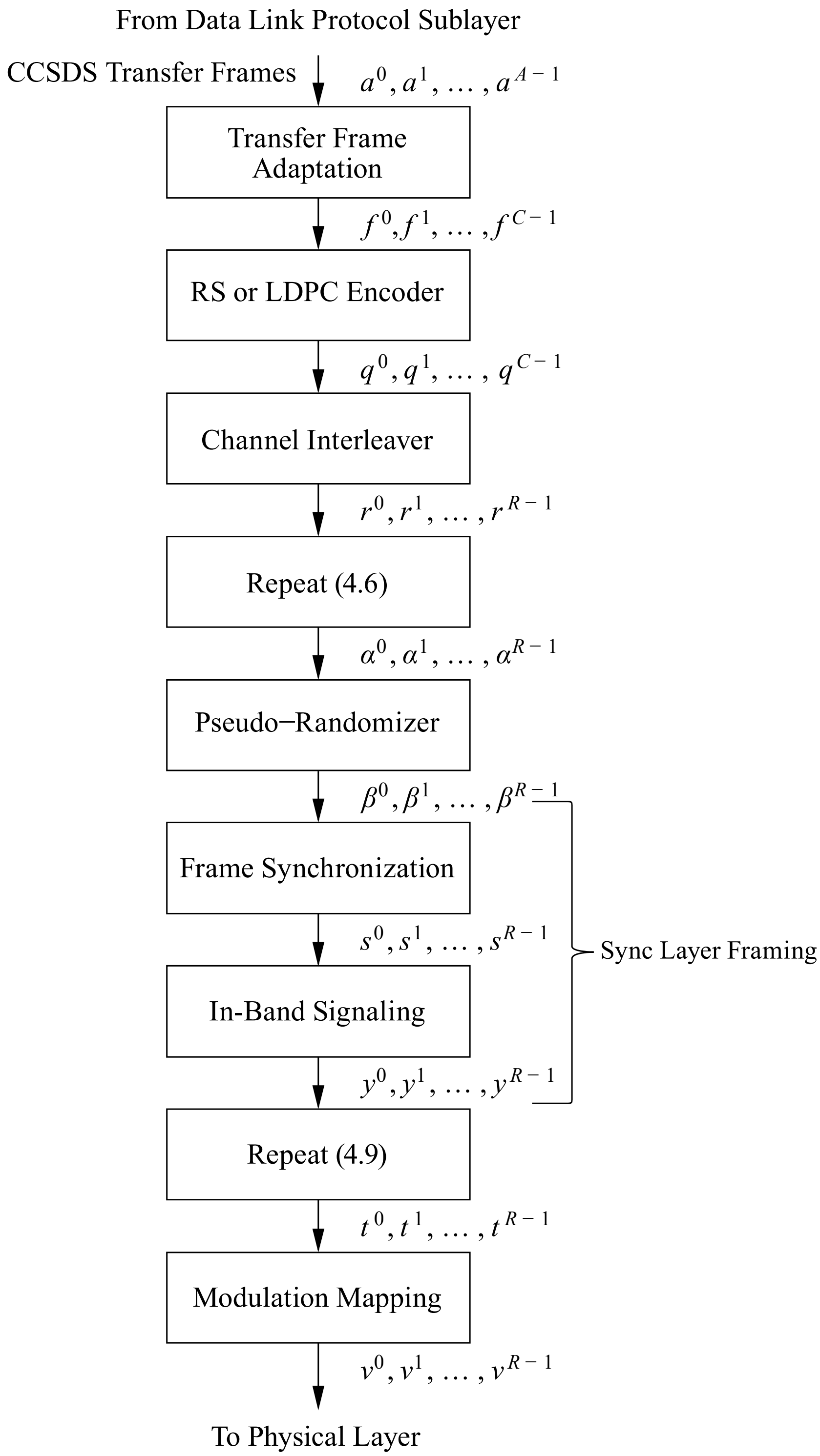


Figure 4-1: O3K Telemetry Signaling

NOTE – For each functional block, lower-case symbols identify the different types of input and output vectors, while upper-case letters represent the number of such vectors.

4.2 CCSDS TRANSFER FRAMES

The input to the Coding and Synchronization Sublayer shall be a sequence of CCSDS transfer frames as described in 3.2.

4.3 TRANSFER FRAME ADAPTATION

4.3.1 OVERVIEW

Transfer frame adaptation is the process of attaching synchronization markers, and slicing the SMTF stream into blocks of an appropriate length for the channel encoder. This produces the correct information block size at the input of the encoder regardless the size of the input transfer frame. When the Data Link Protocol Sublayer provides transfer frames having a length corresponding to the information block size, transfer frame adaptation is not required.

4.3.2 USE OF TRANSFER FRAME ADAPTATION

Transfer frame adaptation may be used for O3K. A managed parameter indicates if transfer frame adaptation is used.

4.3.3 ATTACHED SYNCHRONIZATION MARKER

If transfer frame adaptation is used, an ASM shall be prepended to each transfer frame, resulting in an SMTF, as described in 3.3.

4.3.4 SLICER

If transfer frame adaptation is used, the sequence of SMTFs shall be sliced into information blocks of length k, where k is determined by the code type and code rate (see table 4-1), which are managed parameters. The last information block may be less than k.

Table 4-1: Information Block Sizes

Code Type	Code Rate r	Information block size in bits k
RS	223/255	1784
LDPC	1/2	15360
LDPC	9/10	27648

NOTE – The Data Link Protocol Sublayer ensures that the cumulative size of the transfer frames to be transmitted is compatible with the size of the encoder input.

4.4 CHANNEL CODING

4.4.1 GENERAL

Either an RS encoder or an LDPC encoder shall be used. A managed parameter indicates the code type to be used.

4.4.2 REED-SOLOMON ENCODER

When the RS encoder is used, codeblocks shall be computed from the input blocks as described in section 4 of reference [1], using parameters $E = 16$ and $Q = 0$.

NOTES

1 $E = 16$ corresponds to the (255, 223) RS code.

2 $Q = 0$ means that a shortened codeblock is not used.

3 Reference [1] specifies symbol interleaving with allowed interleaving depths of $I = 1, 2, 3, 4, 5$, and 8.

4 The ASM described in subsection 4.3.10 of reference [2] is not attached to the codeblock.

5 The input to the encoder is I information blocks each of size $k = 1784$ bits (see table 4-1). The output codeblock has size $255 \times I \times 8$ binary digits. The maximum length is equal to $255 \times 8 \times 8 = 16320$ binary digits.

6 In the notation of figure 4-1, the input blocks $\boldsymbol{f} = \boldsymbol{f}^0, \boldsymbol{f}^1, \ldots, \boldsymbol{f}^{C-1}$, with $\boldsymbol{f}^i = f_0^i, f_1^i, \ldots, f_{\hat{k}I-1}^i$, are encoded and interleaved to produce codeblocks $\boldsymbol{q} = \boldsymbol{q}^0, \boldsymbol{q}^1, \ldots, \boldsymbol{q}^{C-1}$, with $\boldsymbol{q}^i = q_0^i, q_1^i, \ldots, q_{255\times I\times 8}^i$.

4.4.3 LOW-DENSITY PARITY-CHECK ENCODER

4.4.3.1 Overview

This specification includes two Quasi-Cyclic (QC) LDPC codes:

– a rate 1/2 Protograph-Based Raptor-Like (PBRL) LDPC code;

– a rate 9/10 Accumulate-Repeat-Accumulate (ARA) LDPC code.

The input to the LDPC encoder is an information blocks of size $k = 15360$ bits for the rate 1/2 code and $k = 27648$ bits for the rate 9/10 code (see table 4-1). For either rate code, the output codeword is $n = 30720$ binary digits. The code rate r is handled by an in-band signaling protocol. The codes are systematic before puncturing is applied and not systematic after puncturing, with the parity-check binary digits appended after the systematic bits.

A QC-LDPC code can be defined by a Parity-Check Matrix (PCM) of size $m_b L \times n_b L$. The PCM of a QC-LDPC will be denoted hereafter **H**, and can be written as an $m_b \times n_b$ array

$$\mathbf{H} = \begin{pmatrix} \mathbf{h_{0,0}} & \cdots & \mathbf{h_{0,\boldsymbol{n_b}-1}} \\ \vdots & \ddots & \vdots \\ \mathbf{h_{\boldsymbol{m_b}-1,0}} & \cdots & \mathbf{h_{\boldsymbol{m_b}-1,\boldsymbol{n_b}-1}} \end{pmatrix}$$

where each submatrix $\mathbf{h}_{i,j}$, $0 \leq i \leq (m_b - 1)$, $0 \leq j \leq (n_b - 1)$, is an $L \times L$ circulant permutation matrix that can be described as an integer power α of the cyclic group generator $\boldsymbol{Z}$ defined as

$$\boldsymbol{Z} = \begin{pmatrix} 0 & 1 & 0 & \cdots & \cdots & 0 \\ 0 & 0 & 1 & 0 & \ddots & \vdots \\ \vdots & & \ddots & \ddots & \ddots & \vdots \\ \vdots & & & & 1 & 0 \\ 0 & & & & 0 & 1 \\ 1 & 0 & \cdots & \cdots & \cdots & 0 \end{pmatrix}.$$

Thus, we have $\mathbf{h}_{i,j} = \boldsymbol{Z}^{\alpha_{i,j}}$ with $-1 \leq \alpha_{i,j} \leq L - 1$. $\boldsymbol{Z}^0 = \mathbf{I}_{\boldsymbol{L}}$ is the identity matrix of size $L \times L$. By convention, $\boldsymbol{Z}^{-1} = \mathbf{0}_{\boldsymbol{L}}$ will denote the all-zero matrix of size $L \times L$. Integer $\alpha_{i,j}$ is referred to as the exponent of the associated circulant $\mathbf{h}_{i,j}$.

Associated with the PCM **H**, we define the exponent matrix $\boldsymbol{H_b}$ of size $m_b \times n_b$ as follows

$$\boldsymbol{H_b} = \begin{pmatrix} \alpha_{0,0} & \cdots & \alpha_{0,n_b-1} \\ \vdots & \ddots & \vdots \\ \alpha_{m_b-1,0} & \cdots & \alpha_{m_b-1,n_b-1} \end{pmatrix}.$$

The specification of $\boldsymbol{H_b}$, therefore, is sufficient to construct $\boldsymbol{H}$, and thus the code.

4.4.3.2 Basic LDPC Code Used in Construction

4.4.3.2.1 The parity check matrix for the LDPC codes shall be formed by using an $\boldsymbol{m_b} \times \boldsymbol{n_b}$ array of $\boldsymbol{L} \times \boldsymbol{L}$ square circulants, where $\boldsymbol{m_b}$, $\boldsymbol{n_b}$, and $\boldsymbol{L}$ are given in table 4-2.

Table 4-2: LDPC Code Parameters

Code Rate	m_b	n_b	L
1/2	140	260	128
9/10	36	252	128

NOTE – The full $m_b L \times n_b L$ parity-check matrix **H** can be constructed from the associated $m_b \times n_b$ exponent matrix $\boldsymbol{H_b}$ with the following procedure:

for $i = 0$ TO $m_b - 1$
  for $j = 0$ TO $n_b - 1$
    $\mathbf{H}(iL{:}\,(i+1)L-1, jL{:}\,(j+1)L-1) = \boldsymbol{Z}^{H_b(i,j)}$
  endfor
endfor

where $\mathbf{H}(i_1{:}\, i_2, j_1{:}\, j_2)$ is the submatrix spanning row indexes i_1 to i_2 and column indexes j_1 to j_2 within matrix **H**.

4.4.3.2.2 The exponent matrix $\boldsymbol{H_b}$ associated with the $\boldsymbol{m_b} \times \boldsymbol{n_b}$ array of circulants in 4.4.3.2.1 shall be as represented in annex C.

NOTES

1 In particular, annex C has one table for the rate 1/2 code, and one for the 9/10 code. Each row of the table has m_b lines. Each row in the table enumerates the position and exponent of all non-zero circulants in the corresponding row of $\boldsymbol{H_b}$. Accordingly, each row $i \in \{0, \dots, m_b - 1\}$ of the table contains at most n_b entries where each entry is a pair $(j, \alpha_{i,j})$ with $j \in \{0, \dots, n_b - 1\}$ being the column index in $\boldsymbol{H_b}$, and $\alpha_{i,j}$ being the exponent of the associated non-zero circulant $\mathbf{h}_{\boldsymbol{i,j}}$.

2 The following procedure may be used to construct $\boldsymbol{H_b}$. First, each exponent matrix $\boldsymbol{H_b}$ is initialized with '−1' in each of the $m_b \times n_b$ entries. Let n_i denote the number of pairs $(j, \alpha_{i,j})$ in row i of the table. There are $2n_i$ total entries in row i of the table. Then the exponent matrix can be built as follows:

for $i = 0$ TO $m_b - 1$
  for $j = 0$ TO $n_m - 1$
    $H_b(i, T(i, 2j)\,) = T(i, 2j + 1)$
  endfor
endfor

3 The structure of the resulting parity-check matrix is as shown in figure 4-2, where the size of the non-zero submatrices A to F for each supported code rate are listed in table 4-3. Submatrices E and F are identity matrices. Submatrix D has the form of a bidiagonal matrix but with the second diagonal starting at line L. For ARA type, the C matrix, F matrix, and the all-zero matrix above F are not used.

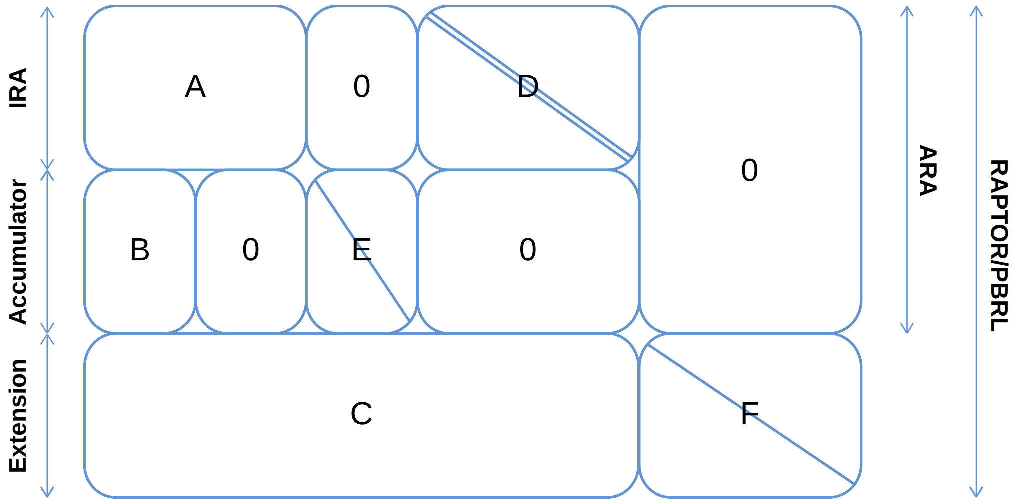


Figure 4-2: General Structure of the Parity-Check Matrix H

Table 4-3: Size of Each Submatrix within H

LDPC Code Rate r	Size of matrix **A** (m_A, n_A)	Size of matrix **B** (m_B, n_B)	Size of matrix **C** (m_C, n_C)	Size of matrix **D** (m_D, n_D)	Size of matrix **E** (m_E, n_E)	Size of matrix **F** (m_F, n_F)
1/2	$40L \times 120L$	$20L \times 20L$	$80L \times 180L$	$40L \times 40L$	$20L \times 20L$	$80L \times 80L$
9/10	$24L \times 216L$	$12L \times 12L$	Not used	$24L \times 24L$	$12L \times 12L$	Not used

4.4.3.3 Encoding from H

4.4.3.3.1 The encoder shall accept as input a block of bits of length $\boldsymbol{k}$ as per table 4-1.

4.4.3.3.2 Codewords consistent with the parity-check matrices in 4.4.3.2.1 shall be produced by the following algorithm.

With $\boldsymbol{u^i} = u_0, \dots, u_{n_bL-1}$ denoting the sequence of codewords resulting from encoding of $\boldsymbol{f}$, where n_bL is the LDPC code length before puncturing, vector $\boldsymbol{u^i}$ can be written as $\boldsymbol{u^i}$ $(\boldsymbol{e^i}, \boldsymbol{p^i})$, with $\boldsymbol{p^i} = (\boldsymbol{p^i_{acc}}, \boldsymbol{p^i_{ira}}, \boldsymbol{p^i_{ext}})$ being the vector of m_bL parity-check bits to compute, where subvectors $\boldsymbol{p^i_{acc}}$, $\boldsymbol{p^i_{ira}}$, and $\boldsymbol{p^i_{ext}}$ have length n_EL bits, n_DL bits, and n_FL bits, respectively (see table 4-3). The systematic encoding of $\boldsymbol{u}$ by **H** can be realized in four steps, as described below:

1 $\boldsymbol{p^i_{acc}} = \boldsymbol{e^i_{acc}} \times \mathbf{B^t}$ is computed, where vector $f^i_{acc} = f^i_0, f^i_1, \dots, f^i_{n_BL-1}$ is formed of the first n_BL bits of input frame $\boldsymbol{f^i}$;

2 $\boldsymbol{p}_{ira}^{i} = \boldsymbol{q}^{i} \times (\mathbf{D}^{t})^{-1}$ is computed, where $\boldsymbol{q}^{i} = \boldsymbol{e}^{i} \times \mathbf{A}^{t}$;

3 $\boldsymbol{p}_{ext}^{i} = (\boldsymbol{e}^{i}, \boldsymbol{p}_{acc}^{i}, \boldsymbol{p}_{ira}^{i}) \times \mathbf{C}^{t}$ is computed;

4 the codeword $\boldsymbol{u}^{i} = (\boldsymbol{e}^{i}, \boldsymbol{p}_{acc}^{i}, \boldsymbol{p}_{ira}^{i}, \boldsymbol{p}_{ext}^{i})$ is formed.

NOTES

1 In step 1 above, n_B refers to the number of columns of matrix $\boldsymbol{B}$, and not the number of columns of the exponent matrix, which is n_b.

2 Because of the particular bidiagonal structure of **D**, simple back-substitution can be used instead of explicitly calculating the inverse $(\mathbf{D}^{t})^{-1}$.

3 The symbol × denotes the matrix product.

4.4.3.4 Puncturing

The LDPC codewords shall be reduced to length $n = 30720$ binary digits by puncturing the first *P* systematic bits, with *P* as given in table 4-4.

Table 4-4: Number *P* of Punctured Bits

Code Rate	*P*
1/2	2560
9/10	1536

NOTE – LDPC encoding produces a systematic codeword of total length $n_b L$. As illustrated in figure 4-3, the first *P* code bits in the LDPC codeword $\boldsymbol{u}^{i}$ are discarded and not transmitted in order to form the codeword

$$\boldsymbol{q}^{i} = u_{P}^{i}, \ \ldots, \ u_{n_B L-1}^{i}.$$

Each $\boldsymbol{q}^{i}$ is called the LDPC codeword.

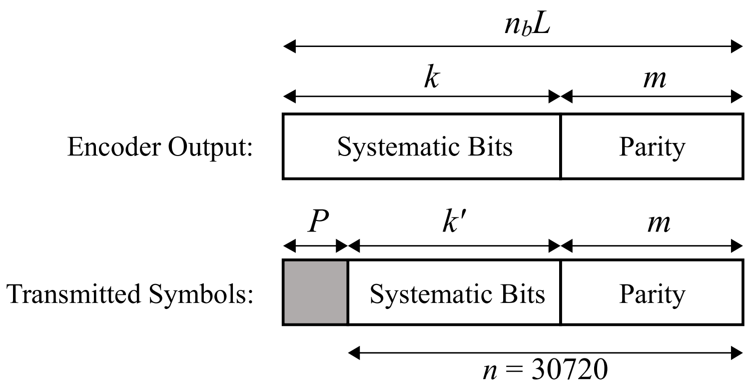


Figure 4-3: Format of the LDPC Codeword after Puncturing

4.5 CHANNEL INTERLEAVER

4.5.1 GENERAL

4.5.1.1 The sequence of RS codeblocks or LDPC codewords $\boldsymbol{q} = \boldsymbol{q}^0, \boldsymbol{q}^1, \ldots, \boldsymbol{q}^{C-1}$ shall be channel-interleaved with a block interleaver as shown in figure 4-4 and described herein.

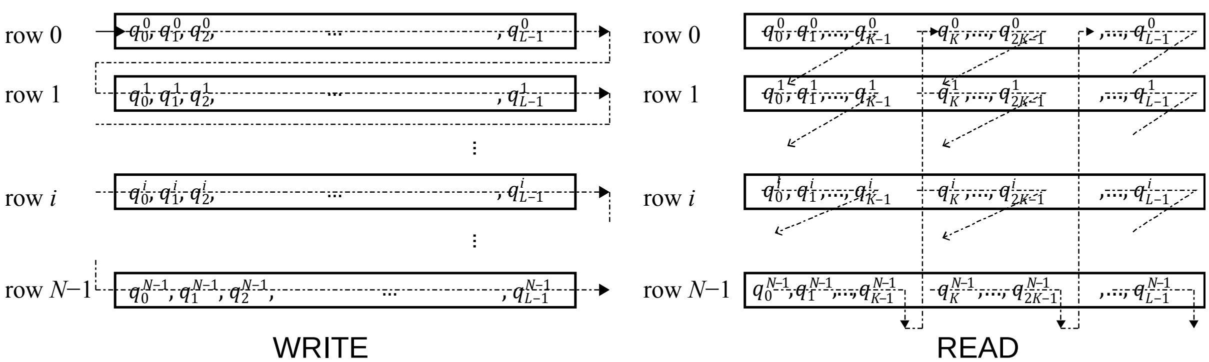


Figure 4-4: Block Channel Interleaver

NOTE – Each codeblock or codeword $\boldsymbol{q}^i$, composed of L bits $\boldsymbol{q}^i = q_0^i, q_1^i, \ldots, q_{L-1}^i$, is written row-wise in the interleaver, and the output is obtained by reading the interleaver column-wise by blocks of length K.

4.5.1.2 The interleaver shall be parameterized with three parameters: $\boldsymbol{K}$, the number of binary digits per interleaver symbol; $\boldsymbol{N}$, the number of rows in the channel interleaver; and $\boldsymbol{L}$, the number of columns in the interleaver.Block interleaver parameters.

4.5.1.3 The values of K, L, and N shall satisfy the constraints in table 4-5.

Table 4-5: Constraints on Block Interleaver Parameters

Code	K	L	N
RS	Multiple of 8; factor of L	$2040 \times I$	At most $2^{23} - 1$
LDPC	{64, 128, 256, 512, 1024}	30720	At most 2^{18}

NOTES

1 L here is not related to the L used in the definition of the LDPC encoder.

2 The parameter K allows more efficient access to memory, compared to a bitwise block interleaver. This can be important in for high-throughput data transfer.

3 N is an integer. The maximum allowable value of N is a compromise between memory hardware constraints onboard and on-ground, and the maximum interleaving time. The maximum N is lower for LDPC than for RS because soft decision decoding at the receiving end requires quantization of the symbols, which takes more memory than the hard-decisions the RS decoder uses.

4 N can be chosen in accordance with the repeat factors *SF* (see 4.6) and q_d (4.9.1) in order to have an interleaving time which is similar for all the selected repeat factors during a mission phase

4.5.2 NUMBER OF ROWS IN THE INTERLEAVER

When RS coding is used, the number of rows in the interleaver, N shall equal either N_N or N_N/q_d; when LDPC coding is used, N shall be signaled by in-band signaling as specified in 4.8.2.6.4.7.

4.5.3 CHANNEL INTERLEAVER INPUT NOTATION

The sequence of RS codeblocks or LDPC codewords $\boldsymbol{q} = \boldsymbol{q}^0, \boldsymbol{q}^1, \ldots, \boldsymbol{q}^{C-1}$ shall be a vector of vectors that can be viewed as a single vector of interleaver binary digits,

$$\hat{\boldsymbol{q}} = q_0, q_1, \ldots, q_{L\times C-1},$$

where for $i \in \{0, 1, \ldots, C-1\}$ and $j \in \{0, 1, \ldots, L-1\}$, $\hat{q}_{L\times i+j} = q_j^i$.

4.5.4 CHANNEL INTERLEAVER OPERATION

4.5.4.1 Write Order and Read Order

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

4.5.4.2 Input and Output Relationship

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 shall be:

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

where $\lfloor x \rfloor$ denotes the integer part of x

4.5.4.3 Reindexing Channel Interleaver Output to Form Interleaved Codewords

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

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

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

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

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

4.5.4.4 Transmission Closure

The Data Link Layer shall ensure that the cumulative size of the transfer frames to be transmitted is compatible with the size of the interleaver.

4.6 REPEAT

4.6.1 When RS coding is used, no repeat shall be applied at this stage (equivalently, $SF = 1$).

4.6.2 When LDPC coding is used, each interleaved block binary digit shall be repeated so that it appears SF times, $SF \in \{1, 2, 4, 8, 16\}$, as follows:

a) for $j \in \{0, 1, \dots, SF(R \times L \times N) - 1\}$, the j^{th} symbol at the output of the repeater shall be

$$\hat{\alpha}_j = \hat{r}_{\lfloor j/SF \rfloor},$$

where $\lfloor x \rfloor$ denotes the integer part of x;

b) the sequence $\boldsymbol{\alpha}$ shall be composed of R blocks each containing $SF \times L \times N$ binary digits:

$$\boldsymbol{\alpha} = \boldsymbol{\alpha}^0, \boldsymbol{\alpha}^1, \dots, \alpha^{R-1},$$

where for $i \in \{0, 1, \dots, R-1\}$, the i^{th} block is denoted $\boldsymbol{\alpha}^i = \alpha_0^i, \alpha_1^i, \dots, \alpha_{SF \times L \times N-1}^i$, and for $j \in \{0, 1, \dots, SF \times L \times N - 1\}$,

$$\alpha_j^i = \hat{\alpha}_{SF \times L \times N \times i + j}.$$

NOTES

1 Each $\boldsymbol{\alpha}^i$ is called a repeated interleaved block.

2 *SF* refers to 'spreading factor'. The repetition, combined with the mandatory pseudo-randomizer (4.7), is a spread spectrum technique. The bit repetition contributes to the Variable Data Rate method as described in 4.8.2.6.2.

3 When LDPC coding is used, the value of SF is handled by inline communications protocol.

4.7 PSEUDO-RANDOMIZER

4.7.1 RANDOMIZATION OF REED-SOLOMON CODEBLOCKS

4.7.1.1 Each interleaved RS codeblock shall be pseudo-randomized by performing the digit-wise modulo-2 addition with a pseudo-random sequence, as shown in figure 3-4 described in 3.5 and herein.

4.7.1.2 For $\boldsymbol{i} \in \{\mathbf{0}, \mathbf{1}, \dots, \boldsymbol{R} - \mathbf{1}\}$, the i^{th} pseudo-randomized interleaved block is denoted $\boldsymbol{\beta}^{\boldsymbol{i}} = \boldsymbol{\beta}_{\mathbf{0}}^{\boldsymbol{i}}, \boldsymbol{\beta}_{\mathbf{1}}^{\boldsymbol{i}}, \dots, \boldsymbol{\beta}_{\boldsymbol{SF} \times \boldsymbol{L} \times \boldsymbol{N} - \mathbf{1}}^{\boldsymbol{i}}$, where for $\boldsymbol{j} \in \{\mathbf{0}, \mathbf{1}, \dots, \boldsymbol{SF} \times \boldsymbol{L} \times \boldsymbol{N} - \mathbf{1}\}$, the j^{th} symbol of the i^{th} block is

$$\beta_j^i = \alpha_j^i \oplus p_j,$$

where $\oplus$ represents modulo-2 addition and p_j is defined in 3.5.2.

NOTE – Each $\boldsymbol{\beta}^i$ is called an RS major code frame.

4.7.2 RANDOMIZATION OF REPEATED INTERLEAVED BLOCKS OF LDPC CODEWORDS

4.7.2.1 Description

Each interleaved repeated block of LDPC codewords shall be pseudo-randomized by performing the digit-wise modulo-2 addition with a pseudo-random sequence, as shown in figure 4-5 and described herein.

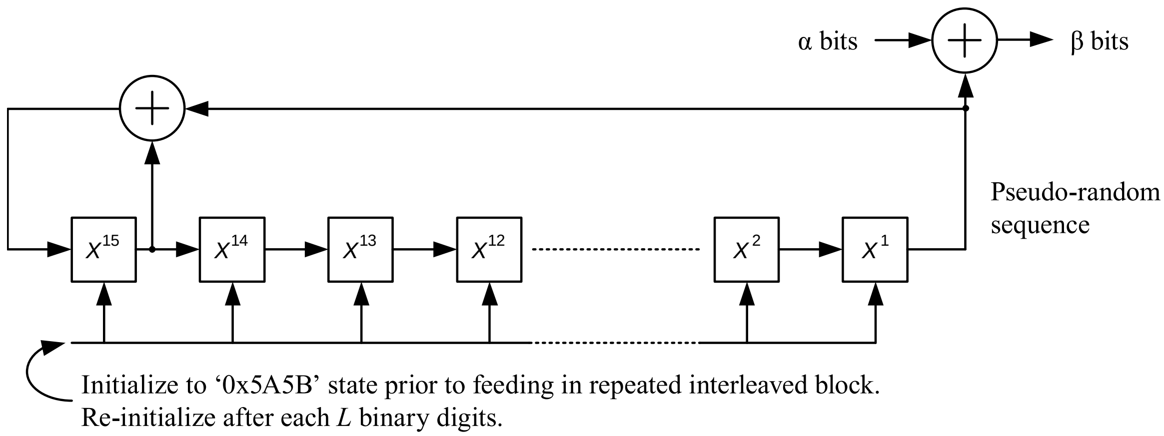


Figure 4-5: Pseudo-Randomizer

NOTES

1 For $\boldsymbol{i} \in \{\mathbf{0}, \mathbf{1}, \ldots, \boldsymbol{R}-\mathbf{1}\}$, the i^{th} pseudo-randomized interleaved block is denoted $\boldsymbol{\beta^i} = \boldsymbol{\beta_0^i}, \boldsymbol{\beta_1^i}, \ldots, \boldsymbol{\beta_{SF\times L\times N-1}^i}$, where for $\boldsymbol{j} \in \{\mathbf{0}, \mathbf{1}, \ldots, \boldsymbol{SF} \times \boldsymbol{L} \times \boldsymbol{N} - \mathbf{1}\}$, the j^{th} symbol of the i^{th} block is

$$\beta_j^i = \alpha_j^i \oplus \gamma_j,$$

where $\oplus$ represents modulo-2 addition, and γ_j is defined in 4.7.2.2.

2 As mentioned before, L = 30720 binary digits.

3 Each $\boldsymbol{\beta^i}$ is called an LDPC major code frame.

4 The pseudo-randomizer defined in this section ensures sufficient randomness and sufficient bit transition density to allow proper synchronization of the decoder.

4.7.2.2 Sequence Specification

The pseudo-random sequence $\gamma_0, \gamma_1, \ \ldots, \ \gamma_{30720-1}$ shall correspond to the first 30720 bits of a truncated PRBS15 sequence generated by the monic polynomial:

$$g(D) = D^{15} + D^{14} + 1.$$

NOTE – The output bit of the sequence is the Least Significant Bit (LSB) of the linear feedback shift register. In figure 4-5, the LSB of the LFSR is denoted x^1.

4.7.2.3 Sequence Initialization

4.7.2.4 This sequence shall begin at the first digit of the repeat interleaved block and the sequence generator shall be reset after each L binary digits. The sequence is continuously repeated until the end of the repeat interleaved block is reached, as illustrated in figure 4-7.

4.7.2.5 The sequence generator shall be initialized with initialization pattern = 0x5A5B.

Index	X^{15}	X^{14}	X^{13}	X^{12}	X^{11}	X^{10}	X^{9}	X^{8}	X^{7}	X^{6}	X^{5}	X^{4}	X^{3}	X^{2}	X^{1}
Value	1	0	1	1	0	1	0	0	1	0	1	1	0	1	1
0x	5			A				5				B			

Figure 4-6: Pseudo-Randomizer LFSR Initialization

NOTE – The first output bits after initialization, using transmission convention (first is MSB) are: 1101 1010 0101 1010 1101 1000 1101 1001 0010 0001 0010 0011.

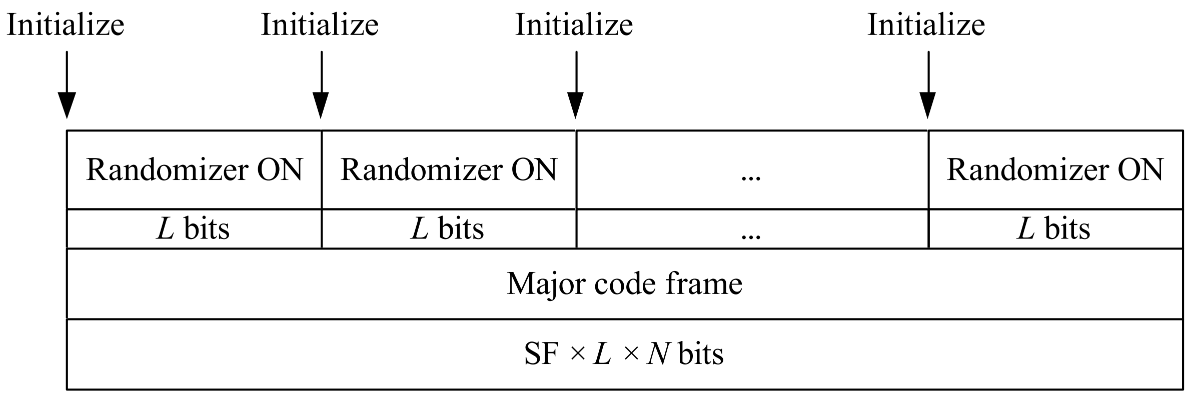


Figure 4-7: Pseudo-Randomizer Initializations Each *L* Bits

4.8 SYNC LAYER FRAMING

4.8.1 SYNC LAYER FRAMING FOR REED-SOLOMON

4.8.1.1 Sync Layer Subframes

Each RS major code frame of $2040\ I\ N$ binary digits shall be split into N_{SF} subframes, each of length $2040\ I\ N_{\mathrm{L}}$ binary digits, where N is a multiple of N_{L}.

NOTES

1 N_{L} is a managed parameter.

2 N_{SF} is computed as $N_{\mathrm{SF}} = N/N_{\mathrm{L}}$, where N is the number of rows of the channel interleaver.

4.8.1.2 Sync Layer Framing with No Subframes ($N_{\mathrm{L}} = N$, i.e., $N_{\mathrm{SF}} = 1$)

4.8.1.2.1 General

When $N_{\mathrm{L}} = N$, that is, when the major code frame is not split into multiple subframes ($N_{\mathrm{SF}} = 1$), then the sync layer frame shall comprise an attached sync layer frame marker as defined in 4.8.2.3.2, followed by the major code frame.

4.8.1.2.2 Sync Layer Frame Marker

The Sync Layer Frame Marker (SLFM) shall comprise a Frame Synchronization Marker (FSM), which corresponds to the ASM as defined in 3.3.2.

4.8.1.3 Sync Layer Framing with Subframes ($N_{\mathrm{L}} < N$, i.e., $N_{\mathrm{SF}} > 1$)

4.8.1.3.1 General

When $N_{\mathrm{L}} < N$, that is, when the major code frame is divided into subframes ($N_{\mathrm{SF}} > 1$), the sync layer frame shall comprise an SLFM, followed by subframe 0, followed by a sequence of Secondary SLFM (SSLFM) and subframe pairs, totaling N_{SF} subframes, as shown in figure 4-8.

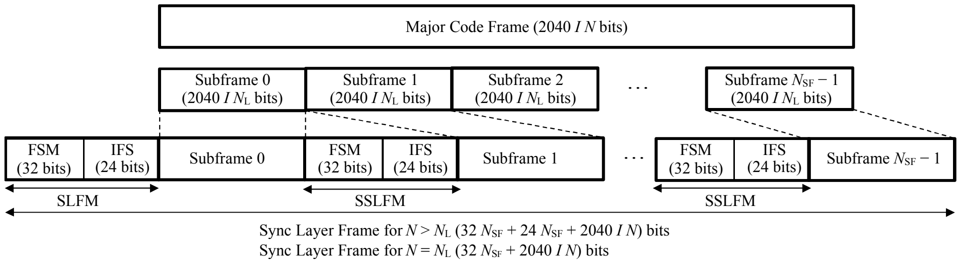


Figure 4-8: Sync Layer Frame for O3K-RS

4.8.1.3.2 Sync Layer Frame Marker

When $N_{\mathrm{SF}} > 1$, the SLFM shall comprise an FSM, which corresponds to the ASM as defined in 3.3.2, followed by an optional Interleaver Frame Signaling (IFS) field, composed of 24 bits: 23-bit counter set to zero (23 zeroes) and one-bit parity set to zero, followed by an optional IFS field, composed of 24 bits: 23-bit counter set to zero (23 zeroes) and one-bit parity set to zero.

NOTE – The presence or absence of the counter is indicated by a managed parameter.

4.8.1.3.3 Secondary Sync Layer Frame Marker

When $N_{\mathrm{SF}} > 1$, the SSLFM shall comprise an FSM, which corresponds to the ASM as defined in 3.3.2, followed by an optional IFS field composed of 23-bit counter and 1-bit counter parity. The value of the counter shall be i in the SSLFM immediately preceding subframe i.

4.8.2 SYNC LAYER FRAMING FOR LOW-DENSITY PARITY-CHECK

4.8.2.1 Sync Layer Subframes

Each major code frame of SF $30720N$ binary digits shall be split into N_{SF} subframes, each of length 30720 N_L binary digits, where $SF \cdot N$ is a multiple of N_L.

NOTES

1 N_{L} is a managed parameter.

2 N_{SF} is computed as $N_{\mathrm{SF}} = SF \cdot N / N_{\mathrm{L}}$, where N is the number of rows of the channel interleaver, and *SF* the repeat factor described in 4.6.

4.8.2.2 Sync Layer Framing with No Subframes ($N_{\mathrm{L}} = SF \cdot N$, i.e., $N_{\mathrm{SF}} = 1$)

When $N_{\mathrm{SF}} = 1$, that is, when the major code frame is not split into multiple subframes, then the sync layer frame shall comprise SLFM as defined in 4.8.2.3.2, followed by the major code frame, as shown in figure 4-9.

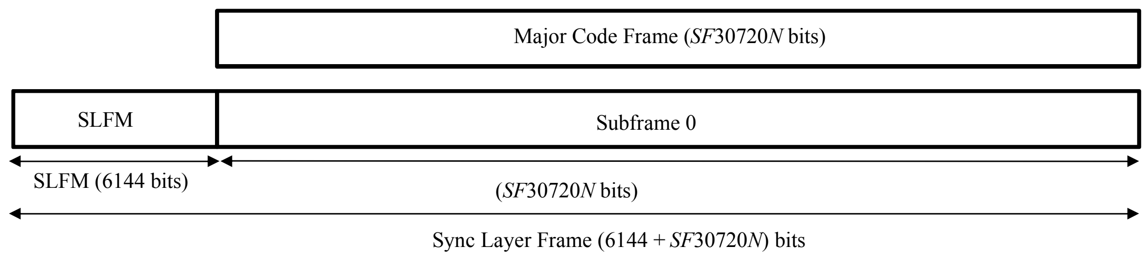


Figure 4-9: Sync Layer Frame for O3K LDPC with No Subframes

NOTE – In this situation, there are no SSLFMs in the sync layer frame.

4.8.2.3 Sync Layer Framing with Subframes ($N_\mathrm{L} < \mathbf{SF} \cdot N$, i.e., $N_\mathrm{SF} > 1$)

4.8.2.3.1 General

When $N_\mathrm{SF} > 1$, the sync layer frame shall comprise a SLFM, followed by subframe 0, followed by a sequence of SSLFM and subframe pairs, totaling N_SF subframes, as shown in figure 4-10.

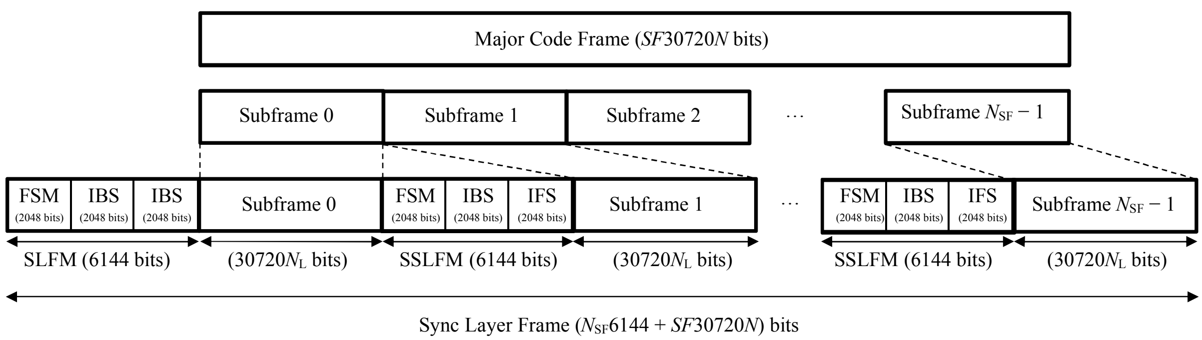


Figure 4-10: Sync Layer Frame for O3K-LDPC with Multiple Subframes

4.8.2.3.2 Sync Layer Frame Marker

4.8.2.3.2.1 General

When $N_\mathrm{SF} > 1$, the SLFM shall comprise an FSM, a first In-Band Signaling (IBS) field, and a second IBS field, as described in the subsections below.

4.8.2.3.2.2 Frame Synchronization Marker

The FSM shall be shall be the 2048-bit sequence defined in annex D, using the initial condition $A = 2$.

NOTES

1 The sequence represented in hexadecimal notation is:

0xC0173D2255032836E2ACAA887EF8668EA64A6911A589AE2E498EC979215A
54575C3D8D71AC679AFBED06D9DAB4B6084B80EC4B3EB7A1A94BD976EE6
7C5612D41813096A8DB50A22B67514E0F90E78F36626E79971105791522CF17C
83374CF7EAD26C7CBA86750F130D1A4D5405141BB35C04BB25EA4F91FE06A
644956088E35E7EB4D510D5842651CFB5CF4039BD2FD4641FF9B47E1453FC1
C7861E510E56BA12A6B5D94CE69346846AFFC4375FB8D4B252F97895A170D2
CDF92F52A6A9F8F1A9ADDCF3C45CB041B3F2FF9A4FEB08DA4DFC793DD14
9E59AC61A76421D7B8FA210071EE4E15F1E199692AE80B47E933E42CDAC123
F5EFB4561B4D1569CE71840

with the left-side bit being the MSB of the FSM to be sent first.

2 This FSM may appear long compared to the traditional CCSDS synchronization marker described in [7]. This length is justified by the need to have a robust start-of-frame synchronization when the repeat factor *SF* (4.6) for the VDR spread spectrum technique is used (see VDR in 4.8.2.6.4.7).

4.8.2.3.2.3 First In-Band Signaling Field

The first IBS field shall be the sequence defined in 4.8.2.6.5.

4.8.2.3.2.4 Second In-Band Signaling Field

The second IBS field shall be identical to the first IBS field.

NOTE – This repeated IBS field indicates the start of a major code frame.

4.8.2.3.3 Secondary Sync Layer Frame Marker

The SSLFM shall be identical to the SLFM defined in 4.8.2.3.2, except that the second in-band IBS field shall be replaced by an IFS field, defined as the 2048-bit sequence defined in annex D, using the initial condition $A = 6$.

NOTES

1 This IFS field indicates all the subframes of a major code frame that are not the first subframe.

2 The SSLFM includes no counter to indicate the position of the subframes inside the block interleaver, as in the RS coding case. It is up to the receiver to detect the beginning of the sync layer frame, signaled by two IBS fields.

4.8.2.4 IDLE Sync Layer Subframes

4.8.2.4.1 General

IDLE Sync Layer (ISL) Subframes (ISLFs) may be generated when needed by the coding and synchronization sublayer to maintain synchronization process at sync layer frame level. When used, they shall have the structure defined in the following subsections and shown in figure 4-11.

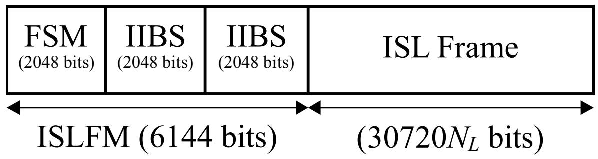


Figure 4-11: IDLE Sync Layer Subframe

4.8.2.4.2 Frame Synchronization Marker

4.8.2.4.2.1 General

The FSM shall be the 2048-bit sequence defined in annex D, using the initial condition $A = 2$.

4.8.2.4.2.2 First IDLE In-Band Signaling Field

The first IDLE In-Band Signaling (IIBS) field shall be the 2048-bit sequence defined in annex D, using the initial condition $A = 4$.

4.8.2.4.2.3 Second IDLE In-Band Signaling Field

The second IIBS field shall be identical to the first IIBS field.

4.8.2.4.2.4 IDLE Sync Layer Subframe Payload

The ISLF payload shall be a vector computed using the pseudo-randomizer defined in 4.7.2. The vector corresponds to the output of the pseudo-randomizer (β bits) when the all 'zeroes' vector of length 30720N_L is provided at the input of the randomizer (α bits).

4.8.2.5 Discussion

The resulting sync layer frame $\boldsymbol{y} = \boldsymbol{y}^0, \boldsymbol{y}^1, \dots, \boldsymbol{y}^{(R+I)-1}$ comprises a combination of $\widehat{\boldsymbol{y}} = \widehat{\boldsymbol{y}}^0, \widehat{\boldsymbol{y}}^1, \dots, \widehat{\boldsymbol{y}}^{R-1}$ sync layer data frames and $\widetilde{\boldsymbol{y}_{idle}} = \widetilde{\boldsymbol{y}_{idle}}^0, \widetilde{\boldsymbol{y}_{idle}}^1, \dots, \widetilde{\boldsymbol{y}_{idle}}^{I-1}$ ISLF, ordered in a monotic way, but where the occurrence of $\widehat{\boldsymbol{y}}^i$ and $\widetilde{\boldsymbol{y}_{idle}}^i$ cannot be known in advance.

An illustration of ISLF insertion is provided by figure 4-12, in which ISLFs are inserted between two consecutive major code frames.

SSLFM	Subframe $N_{SF}-1$	ISLFM	ISLFrame	ISLFM	ISLFrame	⋯	ISLFM	ISLFrame	SLFM	Subframe 0	SLFM	Subframe 1

Figure 4-12: IDLE Sync Layer Subframes Inserted between Two Major Code Frames

The mechanism of ISLFs can be used to ease ground receiver synchronization during acquisition or reacquisition of the link. At the receiver end, ISLFs are discarded.

4.8.2.6 In-Band Signaling

4.8.2.6.1 Overview

In-band signaling is a method to communicate dynamically changing signal parameter values to the receiving end, using the communications link itself. The in-band signaling can be detected at the receiving end, which allows the receiver to recover the parameter values and properly configure itself to receive the remainder of the transmission.

The in-band signaling is accomplished with the IBS. The IBS comprises 2048 binary digits that contain the Mode ID as defined in 4.8.2.6.4, which identifies the emitter configuration table. The IBS is generated using the Gold codes defined in annex D. The set of allowable transmission modes is cataloged in an emitter configuration table known to both the sender and receiver.

In-band signaling is only supported by O3K LDPC coding, where dynamic links are expected. It is not used with HPE. Where dynamic HPE links exist, dynamically changing transmission parameter values could be supported by requiring the receiving end to perform blind acquisition of the changing values, for example, a shift in the PPM order or repeat factor. This is possible within the framework of the HPE standard without utilizing in-band signaling. It is not used by O3K RS either. Where dynamic O3K RS links exist, dynamically changing the symbol rate is supported by requiring the receiving end to perform blind acquisition of the changing value $\boldsymbol{q_d}$, the repeat factor defined in 4.9.1.

4.8.2.6.2 Use of In-Band Signaling

In-band signaling shall be used when LDPC coding is used. It shall not be used when RS coding or SCPPM coding is used.

4.8.2.6.3 Signaled Parameters

When in-band signaling is used, it shall be used to indicate the code rate (r), the repetition factor (SF), the number of rows of the channel interleaver (N), and the size of the channel interleaver block (K).

4.8.2.6.4 Emitter Configuration Table

4.8.2.6.4.1 General

Each distinct parameter set $(r,\ SF,\ N, K)$ used in transmission shall be represented in a row of the emitter configuration table.

NOTES

1 The emitter configuration is defined as a set of parameters that can change dynamically during a mission phase and which values are to be sent to the receiver.

2 The table is a managed parameter known to the transmitting and receiving ends of the link, and held fixed during each mission phase.

4.8.2.6.4.2 Mode ID

Each row of the emitter configuration table shall have a unique numeric Mode ID associated with transmission parameter values $(r, SF, N,\ K)$.

4.8.2.6.4.3 Description

Each row of the emitter configuration table shall have a textual description of the mode.

4.8.2.6.4.4 Code Rate

Each row of the emitter configuration table shall include a code rate $r \in \{1/2, 9/10\}$.

4.8.2.6.4.5 Repetition Factor

Each row of the emitter configuration table shall include a repetition factor $SF \in \{1, 2, 4, 8, 16\}$.

4.8.2.6.4.6 Number of Rows in Channel Interleaver

Each row of the emitter configuration table shall include a number of rows of the channel interleaver N, an integer ranging inclusively from 1 to 2^{18}.

4.8.2.6.4.7 Size of the Channel Interleaver Block

Each row of the emitter configuration table shall include a size of the channel interleaver block $K \in \{64, 128, 256, 512, 1024\}$.

NOTES

1 The in-band signaling is compatible with a static data rate used during the whole mission, a constant data rate used for a specific overflight or mission phase, a dynamic data rate that is predetermined (preprogrammed) based on elevation profile, and a dynamic data rate that is modified in a near real-time fashion to react to observed channel conditions in order to maximize data return.

2 The Mode ID identifies the current configuration of the emitter. If the number of emitter configuration modes defined for a mission phase is high, the IBS detection algorithm may be less robust. During a pass, having only two code rates and 5 different repeat factors, it is not relevant to define more than 6 different configurations.

3 Example emitter configuration tables are given in table 4-6, for the case of a constant data rate, and in table 4-7 for a dynamic data rate scenario.

Table 4-6: Example 1 of Emitter Configuration Mode Table for O3K Optical Communications Using LDPC Coding

Mode ID	Description	Code rate *r*	Repeat factor *SF*	Channel interleaver block K	Number of rows in the interleaver N
0	PL Frame	½	1	128	262144

Table 4-7: Example 2 of Emitter Configuration Mode Table for O3K Optical Communications Using LDPC Coding

Mode ID	Description	Code rate *r*	Repeat factor *SF*	Channel interleaver block *K*	Number of rows in the interleaver *N*
0	PL Frame2_SF16	½	16	128	8192 (65536/8)
1	PL Frame2_SF8	½	8	128	16384 (65536/4)
2	PL Frame2_SF4	½	4	128	16384 (65536/4)
3	PL Frame2_SF2	½	2	128	65536
4	PL Frame2_SF1	½	1	128	65536
61	PL Frame9_SF1	9/10	1	128	65536

4.8.2.6.5 In-Band Signaling Sequence Specification

When Mode ID m is used, $0 \le m \le 61$, the IBS field shall be the 2048-bit sequences defined in annex D, using the initial condition $A = 2(m + 4)$.

NOTE – For example, with the emitter configuration table of table 4-7, the initial conditions A to generate the gold sequences, which identify the configuration, are given in the table 4-8.

Table 4-8: Example of Initial Condition A

Mode ID	0	1	2	3	4	61
Initial condition A	8	10	12	14	16	130

4.9 REPEAT

4.9.1 REPEAT FOR RS

4.9.1.1 When RS coding is used, each coded OOK symbol shall be repeated so that it appears q_d times, where q_d is the repeat factor.

4.9.1.2 For $j \in \{0, 1, \ldots, Sync\_Layer\_Frame\_length - 1\}$, the j^{th} symbol at the output of the repeater shall be

$$t_j = y_{\lfloor j/q_d \rfloor},$$

where $\lfloor x \rfloor$ denotes the integer part of x.

NOTES

1 The minimum slot width of the mission phase is given by the managed parameter T, the telemetry signaling slot width (reference [3]). The repeat factor q_d will make it effectively longer by a factor of $2^{\widehat{w}}$, with $0 \le w \le \left(13 - log_2(T \times 10 \times 10^9)\right)$. After repetition, the resulting effective slot width is one of the slot widths defined in reference [3], subsection 5.7.

2 The repeat factor used by the transmitter is recovered by the receiver itself, and therefore no in-band signaling or management is required.

3 The subset of allowable repeat factors that a mission phase uses is known at the receiving end. This enables the receiver to search over a smaller subset instead of the entire set of allowable repeat factors. This subset is a managed parameter, the Repeat Factor list, defined in table 7-2.

4 The interleaver length can be affected by the repeat factors. The number of rows of the interleaver, N, is defined in the managed parameter and detailed in 4.5.1.2. Its value can either be kept constant, $N = N_{\text{MAX}}$, or it can be scaled with respect to the repeat factors, that is, $N = N_{\text{MAX}}/q_d$. For example, if the maximum data rate selected in the Physical Layer is 10 Gb/s and repeat factors list in the managed parameter is $\boldsymbol{q_d} = \{1, 4, 8\}$: this means that the maximum data rate of 10 Gb/s is transmitted and data rate variation scheme can be used to lower the data rate to 2.5 Gb/s (using $q_d = 4$) and 1.25 Gb/s (using $q_d = 8$).

4.9.2 REPEAT FOR LDPC

When LDPC coding is used, q_d shall be equal to 1, which means that no repetition is applied.

4.10 OOK MODULATION MAPPING

OOK modulation mapping shall be performed by directly mapping the coded binary digits to Non-Return-to-Zero (NRZ)-OOK symbols: coded binary digit 0 gives an NRZ-OOK symbol 0, and coded binary digit 1 gives an NRZ-OOK symbol 1.

4.11 TRANSFER FRAME VALIDATION

4.11.1 OVERVIEW

4.11.1.1 O3K RS

The receiving end of the telemetry transmission detects the symbol rate, obtains timing synchronization, and uses the FSMs to obtain codeword synchronization. After removal of the FSMs, the major code frames are recovered, derandomized, and deinterleaved, and the RS codewords are decoded.

4.11.1.2 O3K LDPC

The receiving end of the telemetry transmission obtains a sync layer frame, and then uses the FSMs to obtain frame synchronization. The IBS of the SLFMs indicates the emitter configuration mode. The IFS of the SSLFMs indicates the presence of a sync layer subframe. The IIBS of the IDLE Sync Layer Subframe Markers (ISLFMs) indicates the presence of an ISLF.

After removal of the sync layer frame markers, SLFM and SSLFM, of the frames containing data, the major code frames are recovered, derandomized, despread, and deinterleaved, and the LDPC codewords are decoded. If frame adaptation is performed, the resulting sequence of SMTFs is synchronized by identifying the ASMs, which are removed, yielding the transfer frames.

ISLFs are discarded by the receiver.

4.11.2 QUALITY INDICATOR

A transfer frame shall be marked valid if it is recovered from one or more correctly decoded codewords (RS or LDPC); a transfer frame shall be marked invalid if it is recovered from one or more incorrectly decoded codewords.

4.11.3 OPTIONAL FRAME ERROR CONTROL FIELD IN TRANSFER FRAME

The FECF defined in reference [1], [2], or [8] is optional, and the system designer may choose to use it for additional frame validation in the Data Link Protocol Sublayer.

4.12 SEQUENCE INDICATOR

A Sequence Indicator shall be ‘zero’ when a transfer frame is the direct successor of the previous one, and ‘one’ when a gap has been detected.

6 OPTICAL RANGING

6.1 OVERVIEW

This Recommended Standard specifies a method to determine the range between a reference point on the ground and a reference point on the spacecraft. This is accomplished by having the optical terminal track a ground-to-space (uplink) signal and transmit a corresponding optical space-to-ground (downlink) signal in such a way that a two-way light-time delay, and thus range, can be discerned.

In the simplest case, the ground transmits what is called a ranging codeword, and the spacecraft receives it and then synchronizes its downlink transmission to the uplink ranging codeword. The ground can then determine the two-way light time by computing the difference between the time the uplink synchronization marker was transmitted and the time the downlink synchronization marker was received (referred to as 'time difference computation'). This is known as the 'synchronous mode' of operation.

This Recommended Standard also specifies an 'asynchronous mode' of operations. In this mode, the spacecraft does not synchronize its downlink transmission with the stream of received uplink ranging codewords. Instead, it measures the phase of the received uplink signal every time a downlink ranging codeword departs. This value is then communicated to the ground, where it can be subtracted from the time difference computation, which achieves the same mathematical result as in the synchronous mode. In the asynchronous mode, care must be taken to ascertain which ranging codewords should be involved in the range computation. Ranging Codeword Identifiers (RCIDs) are used for this purpose.

6.2 UPLINK SIGNAL

The ground station shall transmit one of the following signal types:

a) HPE telemetry signaling in accordance with section 3;

b) O3K telemetry signaling in accordance with section 4;

c) an HPE beacon with accompanying data transmission in accordance with section 5;

d) an RF data signal in accordance with reference [7] or [6]; or

e) an RF signal consisting of a PN sequence in accordance with reference [9].

NOTES

1 An HPE beacon signal without accompanying data is not an allowed transmission for optical ranging.

2 The use of an RF uplink in the synchronous mode of operations is not allowed.

6.3 DOWNLINK SIGNAL

The spacecraft shall transmit one of the following signal types:

a) HPE telemetry signaling in accordance with section 3;

b) O3K telemetry signaling in accordance with section 4; or

c) an HPE beacon with accompanying data transmission in accordance with section 5.

NOTE – Use of an RF downlink is not allowed in optical ranging.

6.4 RANGING CODEWORD

6.4.1 BACKGROUND

A ranging codeword is composed of a given number of synchronization-marked codewords as shown in figure 6-1.

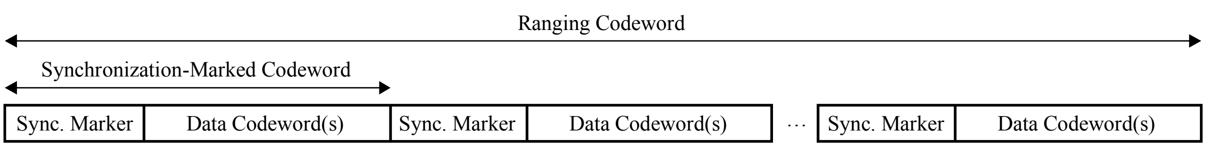


Figure 6-1: Ranging Codeword

The format of a ranging codeword depends on the format of the transmitted signal according to table 6-1.

Table 6-1: Ranging Codeword Structure

Coding and Synchronization Sublayer	Type of Data Codeword	Ranging Codeword Structure
HPE Telemetry	Interleaved	CSM | Interleaved SCPPM CW … CSM | Interleaved SCPPM CW
O3K Telemetry	Interleaved	SLFM | Frame/Subframe/ISL Frame … SLFM | Frame/Subframe/ISL Frame
HPE Beacon + Data	Non-Interleaved	CSM | LDPC Codeword … CSM | LDPC Codeword
HPE Beacon + Data	Interleaved	CSM | Interleaved LDPC CW … CSM | Interleaved LDPC CW
TM	Convolutional Coded (*)	ASM | Transfer Frame … ASM | Transfer Frame
TM	RS Coded	ASM | RS Codeblock … ASM | RS Codeblock
TM	Concatenated Coded (*)	ASM | RS Codeblock … ASM | RS Codeblock
TM	Turbo Coded	ASM | Turbo Codeword … ASM | Turbo Codeword
TM	LDPC Coded (of a transfer frame)	ASM | LDPC Codeword … ASM | LDPC Codeword
TM	LDPC Coded (of a stream of SMTFs)	CSM | LDPC Codeblock … CSM | LDPC Codeblock
TC	BCH Coded	SS | BCH Codeblock + Tail … SS | BCH Codeblock + Tail
TC	LDPC Coded	SS | LDPC Codeblock + Tail … SS | LDPC Codeblock + Tail

NOTES

1 In table 6-1, entries marked with an asterisk (*) indicate that the structure of a ranging codeword is the convolutionally-coded version of the diagram shown in the third column of table 6-1.

2 When the uplink signal consists of a PN sequence, the ranging codeword is not defined.

3 When convolutional or concatenated codes are used, ranging codewords are delimited by the convolutionally-coded form of the ASM.

4 The RCID is the Codeword Identifier (CWID) of the first SMCW in a ranging codeword. The CWID contains the first *S* non-repeated (or non-PN-spread) symbols after the first synchronization marker of any given SMCW, where *S* is determined by the format of the uplink signal according to table 6-2.

Table 6-2: RCID Symbol Size

Space Data Link Sublayer	Coding and Synchronization Sublayer	Number of symbols *S*
TM	TM	32
AOS	TM	48
USLP	TM	112
TC	TC	40
TM	HPE Telemetry	$\lceil 32/\log_2 M \rceil$
AOS	HPE Telemetry	$\lceil 48/\log_2 M \rceil$
USLP	HPE Telemetry	$\lceil 112/\log_2 M \rceil$
AOS	HPE Beacon	48
USLP	HPE Beacon	112
TM	O3K Telemetry	32
AOS	O3K Telemetry	48
USLP	O3K Telemetry	112

NOTES

1 When the uplink signal consists of a PN sequence, the RCID is not defined.

2 With HPE telemetry or HPE beacon with accompanying data, the RCID is the block of *S* PPM symbols immediately following the first codeword synchronization marker in a ranging codeword.

3 With O3K telemetry, the RCID is the block of *S* binary symbols immediately following the SLFM.

4 With an RF signal, the RCID is a block of *S* binary symbols after each synchronization marker or start sequence, which varies depending on the synchronization and coding sublayer technique used (see table 6-1).

5 The receiver implementation might record RCIDs using hard-decision channel symbols (before channel decoding) or symbols reconstructed from first decoded and then re-encoded codewords.

6.4.2 NUMBER OF CODEWORDS PER RANGING CODEWORD

6.4.2.1 There shall be N_u uplink synchronization-marked codewords per uplink ranging codeword, where N_u is a managed parameter that shall be fixed during any given ranging session but may vary across ranging sessions.

6.4.2.2 There shall be N_d downlink synchronization-marked codewords per downlink ranging codeword, where N_d is a managed parameter that shall be fixed during any given ranging session but may vary across ranging sessions.

NOTES

1 In any given ranging session, N_u may be different from N_d.

2 The values of N_u and N_d are selected to meet a mission's range ambiguity requirements.

6.5 MODE OF OPERATION

The optical ranging system may operate in asynchronous or synchronous mode. A managed parameter controls whether the system operates in asynchronous mode or synchronous mode.

6.6 ASYNCHRONOUS MODE

6.6.1 OVERVIEW

In the asynchronous mode of operations, the duration of an uplink ranging codeword need not be related to the duration of a downlink ranging codeword.

6.6.2 MEASUREMENT OF THE RANGING BIT FIELD TIME

6.6.2.1 The spacecraft shall record a ranging bit field a fixed duration after the first synchronization marker in a downlink ranging codeword is transmitted. The format of the ranging bit field is specified in 6.6.3.

6.6.2.2 The ranging bit field shall be transmitted to the ground station in downlink transfer frames.

NOTES

1 An implementation may aggregate several ranging bit fields and transmit them to Earth later, after the ranging activity has concluded.

2 The procedures for placing the ranging bit field in transfer frames is an implementation matter outside the scope of this specification.

6.6.3 RANGING BIT FIELD

6.6.3.1 General

6.6.3.1.1 The spacecraft shall record a ranging bit field using 38 octets as shown in figure 6-2.

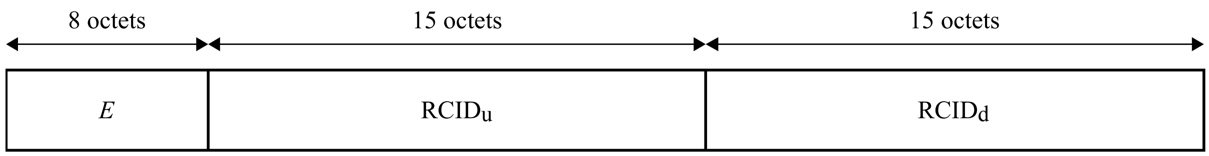


Figure 6-2: Ranging Bit Field

6.6.3.1.2 The first two fields of the ranging bit field shall be formed according to the type of uplink transmission, as indicated in table 6-3.

Table 6-3: First Two Fields of the Ranging Bit Field

Uplink Format	*E*	$RCID_u$
HPE Telemetry	Integer and fractional number of slots elapsed since the start of the uplink ranging codeword.	RCID of the uplink ranging codeword arriving at the receiver when the first field of the uplink phase is measured.
O3K Telemetry		
HPE Beacon + data		
TM	Integer and fractional number of binary symbols elapsed since the start of the uplink ranging codeword.	
TC		
PN sequence	Integer and fractional number of chips elapsed since the start of the PN sequence.	Undefined

6.6.3.2 The Uplink Ranging Phase, *E*

6.6.3.2.1 The uplink range phase *E* shall be a numerical value that relates to the time elapsed since the spacecraft started to receive an uplink ranging codeword or a PN sequence.

6.6.3.2.2 The uplink range phase shall be encoded in the first 8 octets of the ranging bit field.

6.6.3.2.2.1 It shall record the number *E* of slots, symbols, or chips elapsed since the start of the current ranging codeword or PN sequence, times 2^{28}, rounded to the nearest integer, with bit 0 being the MSB and bit 63 being the LSB, and zero padded from the left as necessary.

6.6.3.2.2.2 If the result of *E* times 2^{28}, in binary form, requires more than 8 octets, then the spacecraft shall only encode the 64 least significant bits and discard the rest.

NOTES

1 At the start of a ranging session, the spacecraft receiver is free to choose which uplink codeword is the first codeword within an uplink ranging codeword. A new uplink ranging codeword will begin every N_u codewords thereafter.

2 At the start of a ranging session, the spacecraft receiver is free to choose which downlink codeword is the first codeword within a downlink ranging codeword. A new downlink ranging codeword will begin every N_d codewords thereafter.

3 An implementation may find it useful to set the value of E equal to the measured uplink phase plus a phase offset that has been determined during calibration at the start of the ranging session. This phase offset measures the time delay on board the spacecraft between the arrival of an uplink ranging codeword and the departure of a downlink ranging codeword.

6.6.3.3 The Uplink Ranging Codeword Identifier

6.6.3.3.1 The next 15 octets of the ranging bit field shall record the Uplink Ranging Codeword Identifier ($RCID_u$) (the RCID of the arriving uplink ranging codeword), zero padded on the left as necessary.

6.6.3.3.2 The number of bits needed to encode each symbol in the RCID depends on the format of the uplink signal according to table 6-4, with bit 0 being the MSB and bit 7 being LSB.

6.6.3.3.3 Symbols shall be placed in the bit field in the same order they are read from the ranging codeword.

6.6.3.3.4 If no ranging codeword is present on the uplink, then these 15 octets shall be set to zero.

Table 6-4: Bits per RCID Symbol

Synchronization and Coding Sublayer	Bits per Symbol
TM	1
TC	1
HPE Telemetry	$\log_2 M$
HPE Beacon	1
O3K Telemetry	1

NOTE – If the uplink uses 256-PPM, HPE Telemetry, the RCID

$$\{1,5,100, 255\}$$

is encoded as a sequence of octets $\{s_1, s_2, \ldots, s_{14}\}$, such that

– $s_i = 00000000$ if $i \in \{1, 2, \ldots, 10\}$;

– $s_{11}, s_{12}, s_{13}, s_{14} = 00000001\ 00000101\ 01100100\ 11111111$.

6.6.3.4 The Downlink Ranging Codeword Identifier

The last 15 octets of the ranging bit field shall be used to record the Downlink Ranging Codeword Identifier ($\mathrm{RCID_d}$) (the RCID of the downlink ranging codeword) that triggered latching mechanism that records the uplink phase *E*, encoded using the same convention as 6.6.3.2.

6.7 SYNCHRONOUS MODE

6.7.1 UPLINK AND DOWNLINK SIGNALS

In the synchronous mode of operations, the uplink and downlink signals shall be

a) HPE telemetry signaling in accordance with section 3; or

b) O3K telemetry signaling in accordance with section 4; or

c) HPE beacon with accompanying data transmission in accordance with section 5.

6.7.2 RANGING CODEWORD DURATION

The duration of an uplink ranging codeword shall equal the duration of a downlink ranging codeword, both measured at the spacecraft.

NOTES

1 The managed parameters N_u and N_d are used to control the duration of uplink and downlink ranging codewords, respectively.

2 The values of N_u and N_d can be estimated as follows:

– the duration of an uplink CSM-marked codeword T_u and the duration of a downlink CSM-marked codeword T_d are calculated;

– the minimum duration of a ranging codeword T_min as the least common multiple of the uplink and downlink CSM-marked codeword duration is calculated: $T_\mathrm{min} = lcm(T_\mathrm{u}, T_\mathrm{d})$;

– with A denoting the desired range ambiguity, the multiplicative constant m as $\lceil A/T_{\min} \rceil$ is calculated;

– N_u as $m \cdot T_{min}/T_u$ and N_d as $m \cdot T_{min}/T_d$ are calculated.

6.7.3 RANGING CODEWORD SYNCHRONIZATION

During a ranging session, the spacecraft shall synchronize the uplink and downlink signals in such a way that the start of transmission of a downlink ranging codeword occurs a fixed duration after the leading edge of the first synchronization marker in a received uplink ranging codeword.

NOTE – Spacecraft may measure this fixed offset at the beginning of each ranging session and transmit its value using the ranging bit field defined in 6.7.5.

6.7.4 RANGE SYNCHRONIZATION MARKERS

6.7.4.1 If an uplink ranging codeword is composed of more than one uplink codeword (N_u>1), then the ground station shall periodically replace the CSM in the uplink signal with an alternate pattern, called the Range Synchronization Marker (RSM). The periodicity of RSM replacement, measured in number uplink synchronization-marked codewords, is N_u.

NOTES

1 In the synchronous mode, one uplink RSM-marked codeword together with $N_u - 1$ CSM-marked uplink codewords form an uplink ranging codeword.

2 The system implementer should ensure that the spacecraft's frame synchronizer operates correctly when CSMs are periodically replaced by RSMs.

6.7.4.2 If a downlink ranging codeword is composed of more than one downlink codeword (N_d>1), then the spacecraft shall periodically replace the CSM in the downlink signal with an RSM. The periodicity of replacement, measured in number of downlink synchronization-marked codewords, is N_d.

NOTES

1 In the synchronous mode, one downlink RSM-marked codeword together with $N_d - 1$ CSM-marked downlink codewords form a downlink ranging codeword.

2 The system implementer should ensure that the ground station's frame synchronizer operates correctly when CSMs are periodically replaced by RSMs.

6.7.4.3 If an uplink ranging codeword is composed of more than one uplink codeword (N_u>1), and O3K telemetry is used, then the ground station shall periodically replace the FSM portion of the SLFM with an RSM. The periodicity of RSM replacement, measured in number uplink synchronization-marked codewords, is N_u.

6.7.4.4 If a downlink ranging codeword is composed of more than one uplink codeword (N_d>1), and O3K telemetry is used, then the spacecraft shall periodically replace the FSM portion of the SLFM with an RSM. The periodicity of RSM replacement, measured in number uplink synchronization-marked codewords, is N_d.

6.7.4.5 A link using HPE telemetry shall use the RSM specified in table 6-5.

Table 6-5: RSM for Links Using HPE Telemetry

PPM Order	RSM Value
4	3, 0, 2, 2, 3, 0, 1, 1, 2, 3, 1, 3, 1, 3, 0, 2, 2, 0, 3, 3, 0, 3, 1, 2
8	1, 4, 6, 3, 3, 0, 7, 2, 6, 0, 5, 7, 3, 4, 1, 6
≥16	10, 9, 10, 10, 8, 7, 1, 4, 5, 6, 15, 13, 0, 7, 6, 8

6.7.4.6 A link using HPE beacon with the (128, 64) or (512, 256) LDPC code shall use an RSM of 16 binary symbols. The value of the RSM shall be ED8F, in hexadecimal.

6.7.4.7 A link using HPE beacon with the (2048, 1024) LDPC code shall use an RSM of 64 binary symbols. The value of the RSM shall be 9D44FF6F8D8FA936, in hexadecimal.

6.7.4.8 A link using O3K telemetry with RS encoding shall use an RSM of 32 binary symbols. The value of the RSM shall be 5069DA33, in hexadecimal.

6.7.4.9 A link using O3K telemetry with LDPC encoding shall use an RSM of 2048 binary symbols. The value of the RSM shall be, in hexadecimal:

```
95CB EFFA AB86 AC1D D85C FF0E 78A7 A91B BF79 42F8 BFAC CBFF
AEA8 DDE5 4806 4E38 C32F 6FFE EB92 6A72 0943 EAD9 75E6 12A2
31AD 59B5 828F 6206 A842 D674 6CFB 1C3B 980C 6C00 B2EE 0968
7E19 80FD AE82 D864 C792 29A5 32C9 2B1A 4DD3 EFDF A0B3 BD85
01B5 3DB6 9D93 C179 1EF9 12F3 018A 19FC D350 302E 5E58 1051
33C0 A433 47E2 E9E2 26DB 8B40 AEF9 7826 7949 6F11 D45F 2C80
7F86 0427 405B 8B92 12E1 EA3B 914C 9F08 168A A823 BCE2 9A20
DC31 9A9D 50B1 AEAD 8BBF 1EC6 EA24 A5F7 0357 C02D 72CE E66D
3DA0 D174 BE60 B51E 3E06 8A6F 56EA 13B1 7B8C BC15 8956 C69C
CC3D A57F 5CDE CACA 55D5 FE42 6CCA 5F6B F55D 22BF D457 CBAF
2EBF FA8E AA24 919D 4695 5B75 9612 D2E0
```

6.7.5 RANGING BIT FIELD

6.7.5.1 In the synchronous mode of operations, the ranging bit field is optional. Use of the field shall be controlled by a managed parameter.

NOTE – In the synchronous mode of operation, the ranging bit field can be used encode the phase or time offset between the arrival of an uplink ranging codeword and the departure of a downlink ranging codeword, measured on board the spacecraft at the beginning of the ranging session.

6.7.5.2 The ranging bit field shall be formatted according to 6.6.2.1.

6.7.5.3 The ranging bit field shall be transmitted to the ground station in downlink transfer frames.

NOTE – The procedures for placing the ranging bit field in transfer frames is an implementation matter outside the scope of this specification.

6.8 GROUND MEASUREMENTS

6.8.1 UPLINK TIMING MEASUREMENTS

The Earth station shall record the Earth-transmit time of each uplink synchronization-marked codeword with sufficient accuracy to meet mission specific ranging requirements.

6.8.2 DOWNLINK TIMING MEASUREMENTS

The Earth station shall record the Earth-receive time of each downlink synchronization-marked codeword with sufficient accuracy to meet mission specific ranging requirements.

6.8.3 UPLINK CWID MEASUREMENTS

If operating in asynchronous mode, the Earth station shall record the CWID of each departing uplink synchronization-marked codeword and associate its value with the measurements of 6.8.1, unless the uplink signal is a PN sequence in accordance with reference [9], in which case the uplink CWID is undefined.

6.8.4 DOWNLINK CWID MEASUREMENTS

If operating in asynchronous mode, the Earth station shall record the CWID of each received downlink synchronization-marked codeword and associate its value with the measurements of 6.8.2.

7.2.2 The managed parameters for the O3K with RS coding telemetry signaling shall be those specified in table 7-2.

Table 7-2: Managed Parameters for O3K RS Telemetry Signaling

Managed Parameter	Allowed Values
TM/AOS/USLP transfer frame length (octets)	Integer (max 65536)
Symbol Interleaving Depth (*I*)	1, 2, 3, 4, 5, 8
Repeat factor list	$\boldsymbol{q_d} = \{q_{d,0}; q_{d,1}; \ldots ; q_{d,n}\}$, with $0 \leq n \leq 13$ and $q_{d,i} = 2^w$, with $0 \leq w \leq (13 - \log_2(T \times 10 \times 10^9))$
Interleaver block size K	Multiple of 8 and factor of L
Nominal number of interleaver rows N_N	Integer in the range 1 to N_{MAX} (2^23-1)
Number of rows in the interleaver *N*	N_N; N_N/q_d
Transfer frame adaptation	Used, not used
IFS field (counter)	Used, not used
Number of blocks in a sync layer subframe	N_L

7.2.3 The managed parameters for the O3K LDPC telemetry signaling shall be those specified in table 7-3.

NOTE – The synchronization and channel coding parameters for O3K with LDPC coding are handled both by management and by an inline communications protocol.

Table 7-3: Managed Parameters for O3K LDPC Telemetry Signaling

Managed Parameter	Allowed Values
TM/AOS/USLP transfer frame length (octets)	Integer (max 65536)
The number of blocks of length 30720 within a sync layer subframe, N_L	Integer, N_L=1 to N $\frac{SF \times N}{N_L} \in \mathbb{N}$
Number of rows of the emitter configuration table $N_{ModeTable}$	Integer, 1 to 62
Emitter configuration Mode table (as defined in 4.8.2.6.4)	– Mode ID – Description: text – Code rate, $r \in \{½, 9/10\}$ – Repeat factor $SF \in \{1, 2, 4, 8, 16\}$ – Number of rows in the interleaver N: integer from 1 to 2^{18} – Interleaver block size $K \in \{64, 128, 256, 512, 1024\}$
Transfer frame adaptation	Used, not used

7.3 MANAGED PARAMETERS FOR AOS/USLP TRANSFER FRAME SIGNALING

The managed parameters for a HPE AOS/USLP transfer frame signaling shall be those specified in table 7-4.

Table 7-4: AOS/USLP Transfer Frame Signaling

Managed Parameter	Allowed Values
AOS/USLP transfer frame length (octets)	Integer (max 65536)
Input block length, k	64, 256, 1024
PN spreading factor, q_u	1, 2, 3, 4, 8, 16, 32, 64
Channel interleaver	Used, not used
Number of rows in channel interleaver, N_u	$B_u N_u$ shall be a multiple of 128, which in turn shall be a multiple of N_u.
Shift register length increment in channel interleaver, B_u	

7.4 MANAGED PARAMETERS FOR OPTICAL RANGING

The managed parameters for optical ranging shall be those specified in table 7-5.

Table 7-5: Managed Parameters for Optical Ranging

Managed Parameter	Allowed Values
Uplink and downlink ranging codeword	In the asynchronous mode of operations, N_u and N_d shall be positive integers. In the synchronous mode of operations, N_u and N_d shall be positive integers such that $N_u T_u$ is equal to $N_d T_d$.
Mode of operation	Asynchronous, synchronous
Ranging bit field in synchronous mode	Present, not present

ANNEX C

EXPONENT MATRIX TABLES FOR LDPC CODES

(NORMATIVE)

This annex provides the exponent matrix tables for each of the supported QC-LDPC codes.

Table C-1: Exponent Matrix Table for LDPC Code Rate r = 1/2

10 106 24 97 36 124 50 0 72 42 76 47 78 76 84 42 104 32 108 28 110 114 141 0
11 41 25 38 37 45 51 79 73 87 77 25 79 48 85 11 105 13 109 26 111 108 141 0 142 0
12 4 26 104 38 89 52 94 74 20 78 99 80 40 86 75 106 67 110 98 112 26 142 0 143 0
13 99 27 103 39 82 53 0 61 36 75 123 79 99 87 53 107 2 111 113 113 86 143 0 144 0
14 37 28 38 40 36 54 58 62 76 76 18 80 47 88 103 108 126 112 39 114 118 144 0 145 0
15 101 21 66 29 88 55 78 61 5 63 0 77 115 89 107 109 71 113 100 115 19 145 0 146 0
16 104 22 84 30 15 56 109 62 13 64 108 78 101 90 48 110 68 114 77 116 102 146 0 147 0
17 78 23 8 31 92 57 61 63 9 65 90 79 92 91 112 111 22 115 74 117 48 147 0 148 0
18 96 24 74 32 1 58 105 64 11 66 78 80 28 92 73 112 118 116 22 118 92 148 0 149 0
19 38 25 58 33 87 59 18 61 87 65 96 67 45 93 42 113 123 117 31 119 120 149 0 150 0
20 108 26 120 34 94 60 2 62 6 66 66 68 123 94 46 114 39 118 81 120 17 150 0 151 0
1 109 27 38 35 71 41 47 63 73 67 29 69 19 95 22 101 34 115 36 119 0 151 0 152 0
2 113 28 26 36 115 42 9 64 81 68 7 70 93 96 98 102 22 116 51 120 61 152 0 153 0
3 64 29 70 37 66 43 83 65 67 69 30 71 27 97 109 101 10 103 119 117 27 153 0 154 0
4 107 30 45 38 98 44 99 66 18 70 81 72 88 98 78 102 50 104 46 118 4 154 0 155 0
5 73 31 88 39 50 45 40 67 52 71 40 73 97 99 50 103 24 105 7 119 42 155 0 156 0
6 80 32 50 40 30 46 113 68 72 72 2 74 6 100 5 104 59 106 23 120 44 156 0 157 0
7 78 21 9 33 28 47 5 69 68 73 119 75 95 81 14 101 19 105 9 107 81 157 0 158 0
8 29 22 62 34 55 48 34 70 43 74 120 76 35 82 41 102 60 106 80 108 1 158 0 159 0
9 58 23 13 35 38 49 39 71 108 75 111 77 9 83 41 103 65 107 68 109 68 159 0 160 0
1 27 9 118 10 89 31 15 50 25 59 49 60 5 66 60 81 83 91 80 92 99 113 73 160 0 161 0
2 116 10 2 11 15 32 20 41 124 51 98 60 43 67 30 82 106 92 124 93 66 114 35 161 0 162 0
3 82 11 68 12 72 33 30 41 44 42 118 52 104 68 127 83 1 93 78 94 107 115 122 162 0 163 0
4 95 12 26 13 83 34 8 42 107 43 73 53 108 69 81 84 30 94 25 95 107 116 111 163 0 164 0
5 114 13 4 14 50 35 85 43 40 44 126 54 65 70 70 85 90 95 112 96 100 117 70 164 0 165 0
6 64 14 106 15 49 36 58 44 119 45 110 55 75 71 38 86 54 96 121 97 62 118 56 165 0 166 0
7 75 15 21 16 127 37 67 45 67 46 113 56 36 72 73 87 117 97 52 98 58 119 6 166 0 167 0
8 67 16 28 17 6 38 73 46 106 47 91 57 48 73 91 88 107 98 59 99 81 120 88 167 0 168 0
9 27 17 84 18 46 39 21 47 117 48 117 58 113 74 20 89 18 99 59 100 9 101 107 168 0 169 0
10 80 18 49 19 77 40 41 48 34 49 51 59 68 75 54 81 104 90 127 100 36 102 57 169 0 170 0
11 63 19 93 20 77 21 1 49 50 50 38 60 20 76 41 81 84 82 74 91 10 103 95 170 0 171 0
1 61 12 103 20 59 22 97 41 47 50 2 51 78 77 123 82 81 83 20 92 116 104 85 171 0 172 0
1 31 2 49 13 120 23 13 42 125 51 103 52 34 78 92 83 28 84 72 93 84 105 59 172 0 173 0
2 94 3 103 14 26 24 46 43 4 52 127 53 25 79 65 84 107 85 121 94 112 106 72 173 0 174 0
3 42 4 62 15 110 25 5 44 49 53 67 54 74 80 70 85 2 86 127 95 6 107 28 174 0 175 0
4 60 5 120 16 119 26 85 45 54 54 94 55 105 61 64 86 77 87 42 96 76 108 80 175 0 176 0
5 84 6 92 17 52 27 55 46 35 55 92 56 50 62 117 87 110 88 127 97 19 109 10 176 0 177 0
6 28 7 72 18 54 28 60 47 5 56 117 57 117 63 72 88 49 89 45 98 107 110 118 177 0 178 0
7 21 8 105 19 11 29 64 48 8 57 103 58 26 64 29 89 115 90 19 99 55 111 73 178 0 179 0
8 118 9 102 20 0 30 56 49 66 58 9 59 109 65 16 90 13 91 94 100 12 112 5 179 0 180 0
5 117 12 57 121 0
6 96 13 30 122 0
7 29 14 81 123 0
8 71 15 111 124 0
9 31 16 44 125 0
10 17 17 2 126 0
11 61 18 95 127 0
12 9 19 79 128 0
13 111 20 57 129 0
1 20 14 110 130 0
2 41 15 82 131 0
3 28 16 117 132 0
4 74 17 33 133 0
5 23 18 30 134 0
6 2 19 35 135 0
7 119 20 123 136 0
1 25 8 99 137 0

2 109 9 89 138 0
3 14 10 27 139 0
4 85 11 13 140 0
8 125 12 88 43 0 88 124 153 56 159 105 181 0
9 72 13 52 44 114 89 118 154 16 160 96 182 0
10 83 14 39 45 119 90 79 141 126 155 110 183 0
11 127 15 102 46 42 91 111 142 10 156 87 184 0
12 100 16 37 47 69 92 41 143 69 157 94 185 0
13 105 17 120 48 47 93 12 144 0 158 30 186 0
14 56 18 12 49 84 94 29 145 86 159 29 187 0
15 48 19 97 50 60 95 57 146 23 160 115 188 0
16 65 20 27 51 106 96 98 141 120 147 0 189 0
1 50 17 52 52 32 97 14 142 60 148 101 190 0
2 101 18 105 53 106 98 118 143 10 149 61 191 0
3 48 19 2 54 126 99 50 144 26 150 94 192 0
4 108 20 8 55 54 100 22 145 37 151 24 193 0
1 113 5 74 56 42 81 81 146 121 152 79 194 0
2 78 6 30 57 47 82 42 147 13 153 33 195 0
3 81 7 66 58 47 83 50 148 26 154 61 196 0
4 34 8 101 59 81 84 78 149 70 155 24 197 0
5 59 9 120 60 75 85 94 150 2 156 99 198 0
6 92 10 39 41 61 86 118 151 98 157 22 199 0
7 45 11 58 42 75 87 42 152 52 158 35 200 0
18 78 47 0 56 90 100 78 173 123 201 0
19 20 48 28 57 109 81 51 174 123 202 0
20 62 49 67 58 36 82 30 175 99 203 0
1 3 50 100 59 28 83 55 176 38 204 0
2 33 51 86 60 27 84 117 177 118 205 0
3 41 41 22 52 117 85 115 178 40 206 0
4 75 42 92 53 48 86 31 179 69 207 0
5 20 43 33 54 29 87 13 180 80 208 0
6 14 44 48 55 120 88 63 161 72 209 0
7 109 45 15 56 56 89 4 162 73 210 0
8 42 46 61 57 4 90 104 163 91 211 0
9 85 47 2 58 34 91 7 164 108 212 0
10 65 48 42 59 113 92 30 165 11 213 0
11 70 49 56 60 66 93 108 166 123 214 0
12 45 41 99 50 114 94 81 167 109 215 0
13 62 42 83 51 119 95 4 168 87 216 0
14 125 43 54 52 123 96 118 169 91 217 0
15 55 44 12 53 33 97 1 170 57 218 0
16 110 45 104 54 26 98 83 171 76 219 0
17 48 46 5 55 7 99 34 172 23 220 0
12 2 19 17 26 57 93 102 132 84 155 108 221 0
13 12 20 28 27 63 94 70 133 43 156 29 222 0
1 14 14 124 28 85 95 97 134 95 157 77 223 0
2 81 15 72 29 5 96 70 135 61 158 1 224 0
3 60 16 114 30 31 97 20 136 107 159 118 225 0
4 118 17 47 31 108 98 4 137 124 160 26 226 0
5 95 18 44 32 96 99 8 138 97 141 81 227 0
6 100 19 56 33 14 100 51 139 39 142 47 228 0
7 8 20 109 34 6 81 34 140 7 143 101 229 0
1 51 8 91 35 34 82 45 121 87 144 127 230 0
2 110 9 74 36 80 83 59 122 70 145 67 231 0
3 14 10 18 37 110 84 22 123 65 146 94 232 0
4 15 11 28 38 112 85 33 124 41 147 49 233 0
5 61 12 81 39 42 86 40 125 47 148 34 234 0
6 15 13 112 40 44 87 5 126 58 149 36 235 0
7 65 14 88 21 43 88 107 127 76 150 73 236 0
8 64 15 118 22 6 89 49 128 117 151 122 237 0
9 88 16 12 23 49 90 3 129 104 152 80 238 0
10 87 17 47 24 56 91 6 130 8 153 20 239 0
11 29 18 56 25 120 92 48 131 110 154 96 240 0
12 61 41 124 59 84 94 1 146 15 241 0
13 47 42 67 60 9 95 123 147 48 242 0
14 86 41 12 43 6 96 61 148 45 243 0
15 95 42 23 44 70 97 39 149 6 244 0
16 15 43 90 45 27 98 124 150 88 245 0
17 2 44 84 46 37 99 123 151 4 246 0
18 3 45 55 47 70 100 83 152 101 247 0
19 17 46 75 48 2 81 119 153 60 248 0
20 42 47 121 49 104 82 112 154 104 249 0
1 80 48 8 50 70 83 29 155 42 250 0
2 111 49 57 51 84 84 21 156 99 251 0
3 121 50 9 52 36 85 7 157 101 252 0
4 81 51 88 53 68 86 74 158 1 253 0

5 46 52 84 54 33 87 64 159 82 254 0
6 78 53 103 55 109 88 106 160 114 255 0
7 118 54 20 56 48 89 78 141 111 256 0
8 68 55 23 57 3 90 79 142 6 257 0
9 97 56 5 58 99 91 9 143 27 258 0
10 79 57 110 59 68 92 83 144 75 259 0
11 109 58 36 60 102 93 105 145 108 260 0

Table C-2: Exponent Matrix Table for LDPC Code Rate r = 9/10

6 50 13 101 15 109 16 30 29 102 38 49 39 33 40 64 49 46 61 71 62 63 63 95 82 39 87 42 89 56 96 100 107 32 109 96 111 50 113 9 131 124 135 97 139 101
144 119 152 103 157 37 158 78 159 107 173 84 181 88 184 78 188 119 195 65 205 36 209 113 212 105 229 0
7 8 14 58 16 78 17 106 30 116 39 71 40 39 41 57 50 30 62 125 63 74 64 27 83 69 85 37 88 0 90 74 108 120 110 81 112 99 114 78 132 31 133 63 136 5 140 105
153 43 158 26 159 33 160 112 174 64 182 83 185 43 189 108 196 52 206 69 210 96 213 122 229 0 230 0
8 53 15 86 17 18 18 31 31 93 40 49 41 61 42 48 51 68 63 28 64 7 65 105 84 23 86 12 89 24 91 119 97 81 111 51 113 23 115 3 121 65 134 13 137 16 141 101
154 109 159 25 160 33 161 110 175 42 183 107 186 49 190 17 197 15 207 69 211 121 214 62 230 0 231 0
9 123 16 99 18 45 19 125 32 110 41 6 42 47 43 32 52 98 64 98 65 57 66 46 73 22 87 18 90 41 92 77 98 115 112 126 114 87 116 73 122 23 135 121 138 104
142 53 155 120 160 52 161 45 162 0 176 68 184 113 187 43 191 25 198 101 208 5 212 2 215 46 231 0 232 0
10 26 17 103 19 127 20 25 33 40 42 65 43 42 44 15 53 84 65 34 66 102 67 116 74 34 88 44 91 22 93 81 99 119 113 11 115 72 117 126 123 43 136 47 139 56
143 110 156 2 161 16 162 15 163 61 177 85 185 110 188 34 192 89 199 102 209 105 213 35 216 125 232 0 233 0
11 1 18 7 20 11 21 53 34 114 43 48 44 69 45 118 54 39 66 35 67 84 68 97 75 93 89 126 92 86 94 104 100 16 114 77 116 7 118 52 124 25 137 19 140 24 144 51
145 124 162 26 163 31 164 53 178 13 181 58 186 115 189 54 200 113 205 82 210 52 214 97 233 0 234 0
12 51 19 88 21 119 22 82 35 84 44 114 45 100 46 37 55 52 67 58 68 89 69 20 76 90 90 74 93 85 95 110 101 123 115 84 117 107 119 40 125 102 133 0 138 92
141 93 146 65 163 46 164 46 165 110 179 50 182 28 187 12 190 110 201 29 206 55 211 89 215 21 234 0 235 0
1 117 20 33 22 111 23 111 36 109 45 28 46 25 47 118 56 123 68 120 69 101 70 61 77 95 91 5 94 88 96 36 102 63 116 31 118 2 120 66 126 55 134 67 139 106
142 118 147 65 164 94 165 73 166 124 180 113 183 85 188 108 191 83 202 76 207 97 212 27 216 40 235 0 236 0
2 39 21 30 23 109 24 65 25 14 46 15 47 79 48 122 57 30 69 57 70 88 71 33 78 74 85 33 92 34 95 41 103 118 109 98 117 49 119 108 127 3 135 15 140 79 143
15 148 59 165 97 166 107 167 29 169 26 184 98 189 116 192 30 203 49 205 112 208 54 213 123 236 0 237 0
3 123 13 28 22 120 24 27 26 22 37 21 47 115 48 80 58 49 70 5 71 85 72 82 79 88 86 19 93 117 96 112 104 103 110 118 118 109 120 81 128 13 136 93 141 94
144 100 149 85 166 76 167 114 168 95 170 123 181 9 185 9 190 51 204 31 206 80 209 86 214 95 237 0 238 0
4 106 13 14 14 36 23 14 27 18 37 23 38 89 48 103 59 19 61 43 71 65 72 2 80 73 85 47 87 7 94 23 105 6 109 63 111 103 119 67 129 25 133 26 137 48 142 109
150 70 157 100 167 30 168 2 171 35 182 68 186 97 191 125 193 42 207 42 210 86 215 69 238 0 239 0
5 20 14 93 15 53 24 86 28 11 37 10 38 55 39 116 60 88 61 11 62 124 72 1 81 101 86 91 88 96 95 108 106 71 110 103 112 41 120 33 130 0 134 75 138 114 143
84 151 15 157 40 158 0 168 7 172 93 183 25 187 29 192 76 194 35 208 108 211 102 216 4 239 0 240 0
7 80 11 7 12 127 17 11 26 26 28 72 35 54 42 104 53 114 56 55 57 16 68 17 73 54 77 17 80 0 95 19 99 79 103 101 106 123 119 74 121 85 124 119 129 125 144
23 151 4 154 127 155 62 161 13 170 57 173 73 176 26 186 18 196 28 201 102 203 29 206 110 240 0 241 0
1 42 8 22 12 94 18 111 27 101 29 63 36 43 43 69 54 96 57 38 58 125 69 115 74 62 78 26 81 51 96 87 100 115 104 57 107 110 120 7 122 4 125 77 130 12 133
127 152 56 155 110 156 55 162 106 171 91 174 11 177 17 187 114 197 125 202 7 204 88 207 119 241 0 242 0
1 50 2 36 9 58 19 49 25 40 28 18 30 53 44 115 55 120 58 46 59 47 70 72 75 46 79 70 82 2 85 76 101 60 105 103 108 10 109 26 123 101 126 83 131 20 134 112
145 50 153 99 156 123 163 26 172 24 175 104 178 76 188 118 193 117 198 126 203 45 208 11 242 0 243 0
2 91 3 30 10 38 20 60 26 126 29 119 31 127 45 76 56 66 59 98 60 68 71 22 76 105 80 54 83 51 86 99 97 77 102 44 106 50 110 37 124 85 127 35 132 42 135 17
145 83 146 44 154 77 164 38 173 90 176 56 179 5 189 18 194 19 199 10 204 51 209 17 243 0 244 0
3 111 4 1 11 101 21 43 27 94 30 19 32 68 46 121 49 37 57 74 60 112 72 0 77 48 81 39 84 55 87 39 98 14 103 90 107 115 111 69 121 81 125 125 128 86 136
108 146 4 147 11 155 83 165 97 174 18 177 19 180 73 190 18 193 39 195 100 200 63 210 63 244 0 245 0
4 114 5 68 12 79 22 94 28 56 31 44 33 53 47 36 49 83 50 93 58 60 61 13 73 3 78 45 82 20 88 43 99 89 104 12 108 125 112 105 122 63 126 4 129 58 137 61
147 87 148 52 156 35 166 88 169 76 175 30 178 119 191 56 194 36 196 22 201 39 211 34 245 0 246 0
1 13 5 45 6 77 23 93 29 49 32 112 34 10 48 89 50 37 51 106 59 69 62 22 74 32 79 102 83 72 89 102 97 78 100 106 105 64 113 32 123 57 127 18 130 85 138 20
145 46 148 107 149 76 167 50 170 5 176 64 179 29 192 10 195 22 197 44 202 19 212 103 246 0 247 0
2 72 6 8 7 114 24 89 30 18 33 9 35 67 37 63 51 92 52 92 60 119 63 78 75 13 80 6 84 44 90 15 98 29 101 36 106 61 114 24 124 111 128 41 131 87 139 41 146
125 149 14 150 23 168 32 171 86 177 14 180 5 181 89 196 63 198 84 203 87 213 113 247 0 248 0
3 93 7 79 8 75 13 78 31 19 34 29 36 15 38 15 49 96 52 32 53 90 64 63 73 121 76 33 81 44 91 66 99 49 102 1 107 11 115 13 125 39 129 27 132 12 140 24 147 7
150 34 151 12 157 59 169 82 172 126 178 65 182 18 197 119 199 12 204 127 214 67 248 0 249 0
4 28 8 8 9 125 14 7 25 122 32 109 35 5 39 39 50 113 53 58 54 102 65 23 74 37 77 42 82 13 92 122 100 43 103 113 108 117 116 19 121 72 126 71 130 35 141
92 148 59 151 26 152 13 158 123 170 55 173 117 179 106 183 34 193 47 198 46 200 6 215 107 249 0 250 0
5 101 9 49 10 33 15 89 26 52 33 33 36 93 40 27 51 0 54 20 55 27 66 93 75 116 78 77 83 58 93 18 97 4 101 59 104 72 117 75 122 20 127 56 131 40 142 40 149
18 152 75 153 123 159 109 171 62 174 57 180 21 184 60 194 31 199 107 201 21 216 59 250 0 251 0
6 37 10 85 11 87 16 70 25 74 27 1 34 6 41 91 52 37 55 45 56 124 67 91 76 6 79 1 84 13 94 44 98 113 102 42 105 113 118 87 123 11 128 62 132 84 143 32 150
110 153 117 154 126 160 70 169 119 172 105 175 121 185 55 195 101 200 65 202 113 205 82 251 0 252 0
2 78 12 113 217 0
1 110 3 81 218 0
2 36 4 100 219 0
3 13 5 4 220 0
4 25 6 56 221 0
5 109 7 38 222 0
6 44 8 13 223 0
7 92 9 57 224 0
8 46 10 2 225 0
9 117 11 78 226 0
10 108 12 96 227 0
1 85 11 26 228 0

ANNEX D

GENERATION OF GOLD CODES

(NORMATIVE)

D1 GOLD CODES DEFINITION

D1.1 A Gold code generator shall be used as shown in figure D-1. It corresponds to the Gold code generator used for the real part of non-coherent return PN standardized in subsection 5.3 of reference [9].

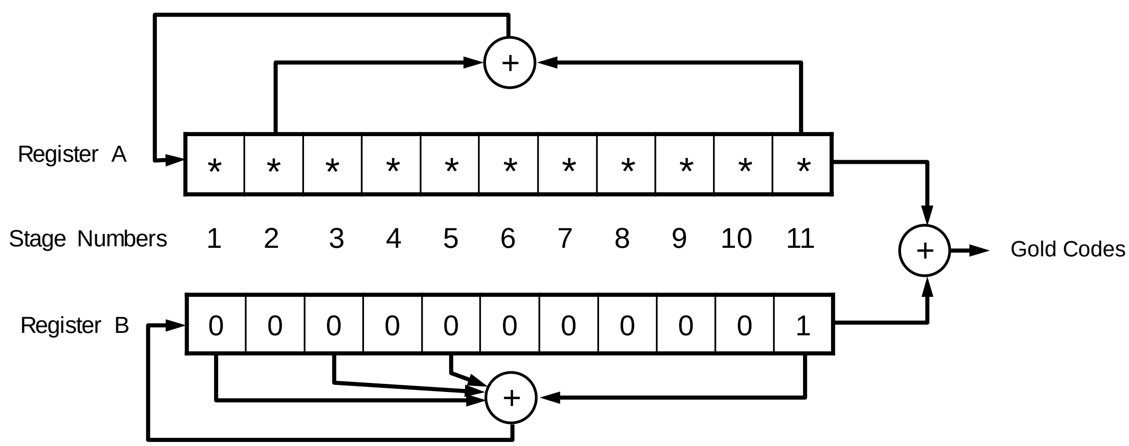


Figure D-1: Gold Sequence LFSRs in CCSDS 415.1-B-1 Publication (Real Part)

D1.2 This circuit shall comprise 2 single-shift registers of length 11, with associated code generator polynomials:

$$g_A(D) = D^{11} + D^2 + 1$$

$$g_B(D) = D^{11} + D^5 + D^3 + D + 1$$

D1.3 A zero shall be appended to the length-2047 Gold sequence to create a sequence of length 2048.

D1.4 The initial condition of register B is fixed; its value shall be [00000000001].

D1.5 The initial condition of registers A shall be defined to produce 65 preferred sequences. The 65 initial conditions correspond to the first 65 even decimals 2, 4, 6, … , to 130, that converted in bits are: [00000000010], [00000000100], [00000000110], … to [00010000010].

NOTES

1 The first sequence, with initial condition of registers A = [00000000010] is reserved for the FSM defined in 4.8.2.

2 The second and third sequences, with initial condition of registers A respectively equal to [00000000100] and [00000000110], are reserved for Physical Layer framing as defined in 4.8.2.6.5.

3 The sequences from number 8 to 130 by step of 2 are the 62 sequences that are used for frame signaling as defined in 4.8.2.6.5.

4 The first 40 binary digits of the first Gold sequence (register A init = 2) are: 1100 0000 0001 0111 0011 1101 0010 0010 0101 0101. The first 40 binary digits of the second Gold sequence (register A init = 4) are: 1010 0000 0001 1000 1100 0011 0100 0100 0000 1111.

5 The provided generator polynomials are shift register polynomials. As explained in reference [G2], various conventions are used to map the polynomial terms to register stages in the shift register implementation. The convention used in reference [G2] and in this annex has the output at the cell with the highest number. If the cell numbering were reversed, the shift register and the output pattern would be the same, but the polynomial representation would be different: $g_{A'}(D) = D^{11} + D^{9} + 1$ and $g_{B'}(D) = D^{11} + D^{10} + D^{8} + D^{6} + 1$. If the numbering convention is misinterpreted, a reverse pattern will be generated.

ANNEX F

ABBREVIATIONS AND TERMS

(INFORMATIVE)

F1 OVERVIEW

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

F2 ABBREVIATIONS

2-PPM binary pulse position modulation

ADU AOS/USLP data unit

AOS Advanced Orbiting Systems

ARA accumulate-repeat-accumulate

ASM attached synchronization marker

BCH Bose-Chaudhuri-Hocquenghem

CRC cyclic redundancy check

CSM codeword synchronization marker

CW codeword

CWID codeword identifier

FECF frame error control field

FSM frame synchronization marker

HPE high photon efficiency

IBS in-band signaling

IIBS IDLE in-band signaling

IFS interleaver frame signaling

ISL IDLE sync layer

ISLF	IDLE sync layer subframe
ISLFM	IDLE sync layer subframe marker
IUT	implementation under test
LDPC	low-density parity-check
LSB	least significant bit
MSB	most significant bit
NRZ	non-return-to-zero
O3K	optical on-off keying
OOK	on-off keying
OSI	Open System Interconnection
OTM	optical telemetry
PCM	parity-check matrix
PBRL	protograph-based raptor-like
PICS	protocol implementation conformance statement
PLOP	Physical Layer Operations Procedure
PN	pseudo-random noise
PPM	pulse position modulation
PRBS	pseudo-random binary sequence
QC	quasi-cyclic
RCID	ranging codeword identifier
$RCID_d$	downlink ranging codeword identifier
$RCID_u$	uplink ranging codeword identifier
RF	radio frequency
RS	Reed-Solomon
RSM	range synchronization marker

SCPPM	serially concatenated convolutionally coded pulse position modulation
SF	repeat factor/spreading factor
SLFM	sync layer frame marker
SLFRAME	sync layer frame
SMCW	synchronization-marked codeword
SMTF	synchronization-marked transfer frame
SSLFM	secondary sync layer frame marker
TM	telemetry
USLP	Unified Space Data Link Protocol

F3 TERMS

channel symbol: The unit of output of the innermost encoder.

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: Of an (n,k) block code, a sequence of n channel symbols that are produced by encoding a sequence of k information symbols.

Coding and Synchronization 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.

constraint length: In convolutional coding, the number of consecutive input symbols needed to determine the value of the output symbols at any time.

convolutional code: A code in which a number of output symbols are produced for each input symbol. Each output symbol is a linear combination of the current input bit and some or all of the previous $k-1$ input bits, where k is the constraint length of the code.

slot measurement: Receiver estimate of the intensity of light, number of photons observed, or related statistic in a slot of the received transmission.

synchronization-marked transfer frame, SMTF: The data unit that consists of the ASM and the transfer frame.

ANNEX G

INFORMATIVE REFERENCES

(INFORMATIVE)

[G1] B. Moision and J. Hamkins. "Coded Modulation for the Deep-Space Optical Channel: Serially Concatenated Pulse-Position Modulation." *IPN Progress Report* 42-161 (May 15, 2005).

[G2] *Data Transmission and PN Ranging for 2 GHz CDMA Link via Data Relay Satellite.* Issue 1. Report Concerning Space Data System Standards (Green Book), CCSDS 415.0-G-1. Washington, D.C.: CCSDS, April 2013.

NOTE – Normative references are listed in 1.9.