The Consultative Committee for Space Data Systems

Proposed Draft Recommendation for
Space Data System Standards

HIGH DATA THROUGHPUT: CODING AND SYNCHRONIZATION

PROPOSED DRAFT RECOMMENDED STANDARD

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[Foreword text specific to this document goes here. The text below is boilerplate.]

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PREFACE

This document is a draft CCSDS Experimental Standard. Its 'White Book' status indicates that its contents are not stable, and several iterations resulting in substantial technical changes are likely to occur before it is considered to be sufficiently mature to be released for review by the CCSDS Agencies.

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

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

DOCUMENT CONTROL

Document	Title and Issue	Date	Status
CCSDS 000.0-W-0	High Data Throughput: Coding and Synchronization, Proposed Draft Recommended Standard, Issue 0	October 2014	Current draft
CCSDS 000.0-W-0	High Data Throughput: Coding and Synchronization, Proposed Draft Recommended Standard, Issue X	March 2015	Removed HDLC encapsulation
CCSDS 000.0-W-0	High Data Throughput: Coding and Synchronization, Proposed Draft Recommended Standard, Issue X.1	October 2015	Added details of physical layer headers

CONTENTS

Section Page

1 INTRODUCTION

1.1 PURPOSE

[Insert introductory subsections such as PURPOSE, SCOPE, APPLICABILITY, RATIONALE, etc. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for the contents of section 1.]

1.2 SCOPE

1.3 APPLICABILITY

1.4 RATIONALE

1.5 DOCUMENT STRUCTURE

1.6 DEFINITIONS

The following definitions are utilized in this document.

Table 1: Definition of Terms.

Term	Definition
Bit	A unit of information transferred between data link protocol sublayer and the sync and channel coding sublayer
Code symbol	An indivisible entity transferred between the sync and channel coding sublayer and the physical layer
Channel symbol	An optical waveform used to transmit information within a unit interval (i.e., indivisible output of physical layer)
Off time	Unit time interval between channel symbols or groups of channel symbols in which no information is conveyed via an optical transmission
Burst period	Periodic interval including a single off time and an associated preceding channel symbol or group of channel symbols
Data rate	The average rate of bit transmission
Channel	The average rate of channel symbol transmission

symbol rate	
Bandwidth expansion	The ratio of the channel symbol rate to the data rate
Channel clock rate	The maximum instantaneous rate of channel symbol transmission

1.7 REFERENCES

The following publications contain provisions which, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this Experimental Standard are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

[Only references required for the implementation of the specification are listed in the References subsection. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for additional information on this subsection.]

[1] CCSDS 732.0-B-3, “AOS Space Data Link Protocol,” Blue Book. September 2015.

[2] ETSI EN 302 307 DVB-S2 Standard, version

2 OVERVIEW

[Non-normative overview text appears in section 2. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for the contents of section 2.]

3 DATA LINK LAYER

[Normative specifications appear in sections 3 through *n*. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014).

All sections and annexes should be separated by Word continuous section breaks.]

3.1 TERMINAL A

3.1.1 CCSDS TRANSFER FRAMES

Processing for each data stream will consist of a slicer, an encoder, an interleaver, a Q-Repeater, and a physical framer, as shown in Figure 3-1. A data stream (bits) and a fill stream will be merged by the physical frame merger.

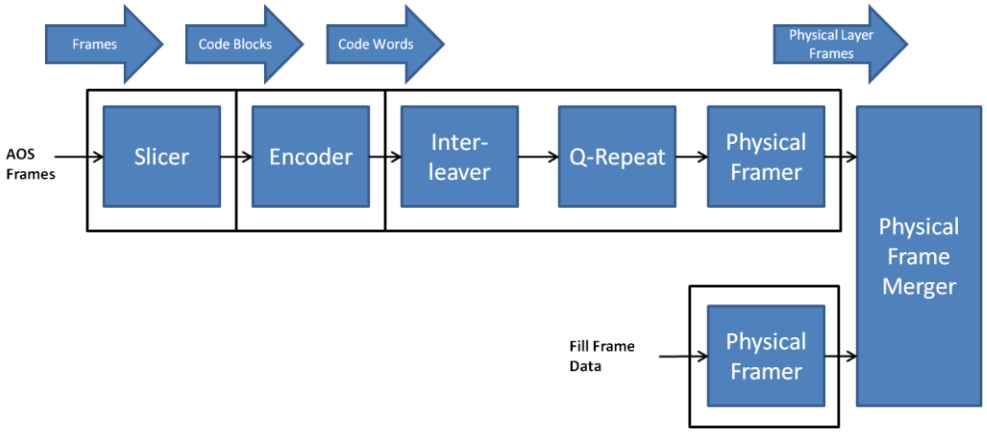

Figure 3-1. Transmitter Processing Sequence for Ground Relay or User Terminal

The input to the coding and synchronization sublayer shall be a sequence of fixed-length CCSDS AOS Transfer Frames as specified in Ref. [1].

The AOS frames input to the coding and synchronization sublayer shall be 16104 bits.

3.1.2 SLICER

The incoming AOS frames are sized such that the length of two AOS frames exactly matches the number of information bits for the input block size for the channel coder described in Section 3.1.3.

The slicer shall generate input blocks to the channel coder by concatenating two consecutive AOS frames.

No insertion of additional synchronization markers is required.

3.1.3 CHANNEL CODING

Rate-1/2 DVB-S2 channel encoding shall be applied to the code blocks in accordance with ETSI EN 302 307 Section 5.3 [1]. Binary digit interleaving, as described in Section 5.3.3 of ETSI EN 302 307, is not applied; only the DVB-S2 LDPC inner code and the BCH outer code are employed.

The input block size to the rate-1/2 encoder is 32208 information bits. Additional DVB-S2 code rates can be selected by the user if coordinated with the remote end of the link (typically the Ground Relay). These additional code rates could range from rate-1/4 to rate-9/10, which have input block sizes ranging from 16008 information bits to 58192 information bits, respectively. Note that changing the input block size also requires changing the AOS frame size and/or the method for slicing the incoming AOS frames.

For the 2.88 GHz slot rate, the code shall use normal FECFRAME (nldpc = 64,800 bits) output block size and LDPC code rate of 1/2.

3.1.4 CHANNEL INTERLEAVING

3.1.4.1 Overview of Interleaving

Interleaving is used to mitigate the burst errors associated with fades caused by the dynamic channel.

Convolutional interleaving and deinterleaving shall be used on all data links between a terminal within the atmosphere (Ground or Airborne Users, Ground Relay) and a Space Relay.

A block diagram of the convolutional channel interleaver and deinterleaver is shown in Figure 3-2. Channel interleaving acts over several codewords so that the channel symbol rate (and thus link rate) of the system is not affected by interleaving. In the context of Figure 3-2 there is one bit out of the interleaver (respectively, deinterleaver) for each input bit. There is, however, a fixed delay associated with the interleaving process, and its value is a function of the interleaving parameters. Note that the deinterleaver in the figure is consistent with hard-decision decoding, and is shown as an example implementation for the purpose of illustration; soft-decision decoding is also a valid implementation.

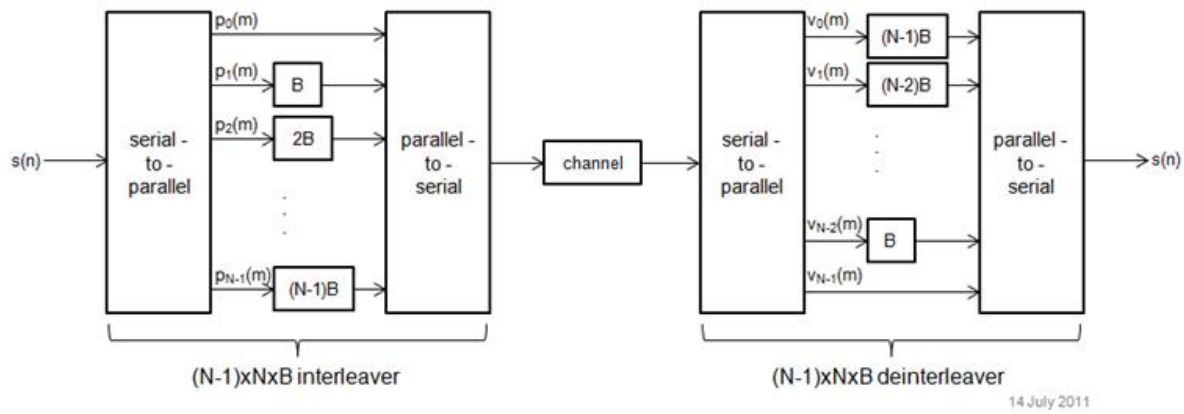

Figure 3-2. Convolutional Channel Interleaver and Deinterleaver

3.1.4.2 Description of Interleaving Process

The convolutional interleaver performs interleaving on a continuous basis as conceptually illustrated in Figure 3-2.

The interleaving is performed on a binary digit basis. Let the i-th codeword output of the encoder be denoted $c_i[0]$, $c_i[1]$, $c_i[2]$,…$c_i[J-1]$, where $c_i[0]$ is the first output binary digit from the encoder and J is the length of the codeword. A continuous stream of binary digits, s(n), n=0,1,2,…, is formed by serially concatenating successive codewords, i.e., s(0), s(1), … = $c_i[0]$, $c_i[1]$, $c_i[2]$,…$c_i[J-1]$, $c_{i+1}[0]$, $c_{i+1}[1]$, $c_{i+1}[2]$,…$c_{i+1}[J-1]$, $c_{i+2}[0]$,…, and this stream serves as input to the channel interleaver, with $s(0)=c_i[0]$ being the first input bit.

The sequence s(n) is input to a serial-to-parallel converter that outputs N parallel streams, $p_k(m)$, k=0,1,...,N-1, m=0,1,…, where each stream is simply one of the N phases of the serial input sequence; i.e., $p_k(m) = s(mN + k)$. The k-th stream is input to a kB stage delay line, which is clocked once every N binary digit times. The output of the N delay lines is serialized for channel transmission.

At the receiver, the deinterleaver accepts the (potentially Q-recombined) data stream into a serial-to-parallel converter with N outputs. The N output streams are denoted $v_k(m)$, k=0,1,...,N-1, m=0,1,…. The k-th stream is the input to an (N-1-k)B stage delay line, which is clocked every N binary digit times.

The overall delay to the serialized output stream is thus (N-1)NB binary digit times. Thus, starting at the (N-1)B-th sample output from the deinterleaver, the deinterleaved data stream corresponds to the binary digits $c_i[0]$, $c_i[1]$, $c_i[2]$,…$c_i[J-1]$, which is the i-th codeword. The memory required at the transmitter (respectively, receiver) for interleaving (respectively, deinterleaving) is N (N-1)B/2.

3.1.4.3 Interleaver Parameter Value

The interleaver parameter, N, shown in Figure 3-2, evenly divides the length of the physical layer frame payload which is 64,800 bits long. The physical layer frame payload is the same

length as one DVB-S2 codeword (see section 3.1.3). By design, the first binary digit of each codeword is always input to the top delay line of the interleaver, denoted $p_0(m)$ in Figure 3-2. Therefore, the payload for a new physical layer frame is output after each codeword has been fully fed into the channel interleaver. Similarly, the first binary digit of the deinterleaver output after each physical layer frame payload has been fully fed into the channel deinterleaver contains the first binary digit of a codeword. This allows the convolutional interleaver to be self-synchronizing in the sense that each physical layer frame input to the deinterleaver will result in a single codeword output from the deinterleaver.

For interleaved burst-mode links, codewords shall be interleaved using a convolutional interleaver as follows:

The input to the interleaver is a sequence of codewords, and the output consists of interleaved bit sequences.

- The convolutional interleaver has N delay lines, numbered 0 through N-1.

- The delay of the ith delay line is (i - 1)B, where B is measured in binary digits.

- All binary digits from a codeword are written sequentially into the delay lines, starting with the MSBD of the codeword being written into delay line 1.

- For every codeword written into the interleaver, an interleaved bit sequence consisting of 64,800 bits is read out of the interleaver (an interleaved codeword).

- At the output of the interleaver, binary digits are read sequentially out of the delay lines, starting with the MSBD of the interleaved bit sequence being read out of delay line 1.

Note: The MSBD of an interleaved codeword (64,800 binary digits) is also the MSBD of some codeword (other binary digits in the sequence may or may not belong to the same codeword).

Note: This requirement is not intended to specify an implementation. Any implementation that meets the requirements and complies with this interface definition is acceptable.

The parameters for the convolutional interleaver depend on the interleaver mode and shall be as defined in Table 3-1.

Table 3-1. Convolutional Interleaver Parameters

Nominal Data Mode	Interleaver Mode	N	B (binary digits)
U-311	CONV_162_24000	162	24,000
U-155	CONV_162_11200	162	11,200
U-51.8	CONV_162_4000	162	4,000
U-16	CONV_162_1216	162	1,216
U-8	CONV_162_608	162	608
U-4	CONV_162_288	162	288
U-2	CONV_162_224	162	128

The interleaver mode shall be one of the allowed interleaver modes for the current system data rate mode, as listed in Table 3-2.

Table 3-2. Allowed Interleaver Modes

Mode Name	Allowed Interleaver Modes
U-1244	CONV_162_96000
U-622	CONV_162_48000
U-311	CONV_162_24000
U-155	CONV_162_11200
U-51.8	CONV_162_4000
U-16	CONV_162_1216
U-8	CONV_162_608
U-4	CONV_162_288
U-2	CONV_162_128

Space Relay telemetry and command streams are interleaved separately from user data streams.

For modes that require Q-repetition (U-16, U-8, U-4, U-2), as described below in section 3.1.6, the interleaver depth (nominally 1 second) is reduced by a factor of Q.

3.1.5 MAPPER (SYMBOL TO CHANNEL SYMBOL)

3.1.6 Q-REPETITION

Q-Repetition is additional coding applied in the form of multiple copies of each data frame.

Only system modes identified in Table 3-3 shall have Q-repetition.

The repetition value for data rates with Q-repetition shall be as listed in Table 3-3.

Table 3-3. Q-Repetition

Data Mode	Repetition Value
U-16	2
U-8	4
U-4	8
U-2	16

The unique word and data payload shall be the same for all Q-repetition data frames.

3.1.7 PHSYICAL LAYER FRAME HEADERS

Physical layer frames are used to transport five types of data: User data, User Terminal telemetry, Space Relay command, Space Relay telemetry, and fill data. User data and telemetry frames carry User data (bits) and telemetry over the edge-to-edge link. Space Relay command and telemetry frames carry Space Relay commands and telemetry between a Ground Relay and a Space Relay. Fill frames are used to fill links to a constant channel rate and to allow asynchronous clock domains.

Note: This physical layer framing is not to be confused with the physical layer framing in the DVB-S2 ETSI EN 302 307 standard [1].

Physical layer framing is used for the following purposes:

- Demultiplex different frame types propagating to and from a Space Relay
- Allow asynchronous clock domains between terminals
- Demultiplex user data frames into individual data streams at the Ground Relay
- Identify frame gaps for proper de-interleaving
- Carry channel state information provided by the Space Relay demodulator on multi-hop links for proper decoder input computations in the end-point terminal
- Identify fill frames

Physical layer framing shall be performed on fill frames and each encoded and interleaved AOS-framed bit stream. There is a separate data (bit) stream associated with each unique word.

The physical layer frame structure shall be composed of the following fields (from MSBD to LSBD) as shown in :

- unique word (384 binary digits),
- control data (640 binary digits),
- frame data (64800 bits)

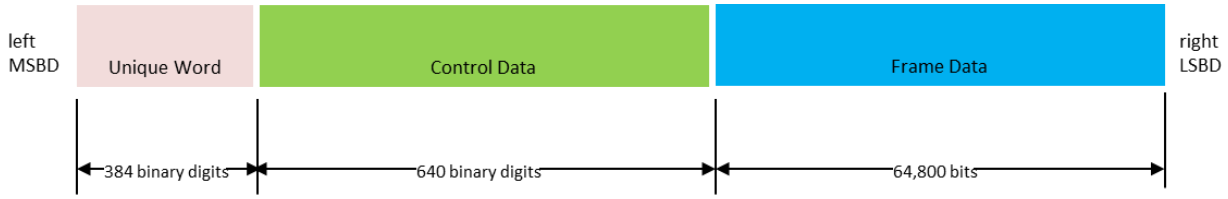

Figure 3-3. Physical Layer Frame Structure

3.1.7.1 Unique Word

An identifier, called the "unique word," is applied to the frames at the physical layer to allow for frame synchronization, channel state computation, and for traffic to be multiplexed, demultiplexed, and switched appropriately at the physical layer.

The unique words used are managed parameters. Unique word values are assigned by mission planning. It is desirable for the set of unique words to exhibit good autocorrelation and cross-correlation properties.

The unique word shall be a 384 binary digit sequence.

The leftmost 96 binary digits of each 384 binary digit sequence shall be the following constant, fixed across all unique words: 0xEBE2 587B 22EE 5319 A15A A382

Note: The 96 binary digit sequence above provides good autocorrelation properties, a DC balance of two, and a maximum run length of five; it is intended to be used as a frame alignment signal.

As shown in , the "leftmost" or "MSBD" of the unique word shall be located in the "leftmost" or "MSBD" binary digit of the physical layer frame header.

Each User link uses two unique words in each direction (four total), one for data frames and one for fill frames.

Frames identified as fill on a multi-hop link are removed and shall not be passed along to the next hop.

For each data frame received on a multi-hop data link, a terminal shall replace the received data unique word with an error-free copy of the unique word that had a maximum correlation with the received unique word before transmitting over the next hop.

The telemetry stream generated by a Space Relay uses another unique word. The Space Relay multiplexes the User data link data stream(s) and the Space Relay telemetry stream together for transmission to a Ground Relay. Each hop uses an additional fill frame unique word.

Frames identified as fill at the last terminal in a multi-hop link are removed and shall not be output to the data edge interface.

The command stream from a Ground Relay to a Space Relay also uses a unique word, as does the fill frame for that link. For this link, the Space Relay demultiplexes the user data stream(s) from each other and the Space Relay command stream.

Frames identified as fill at a User Terminal are removed in the User Terminal and shall not be output to the user platform.

3.1.7.2 Control Data

The 640-binary-digit Control Data field consists of three subfields, as shown in : Channel State Information (128 binary digits), Frame Sequence Number (384 binary digits) and Physical Layer Control Information (128 binary digits).

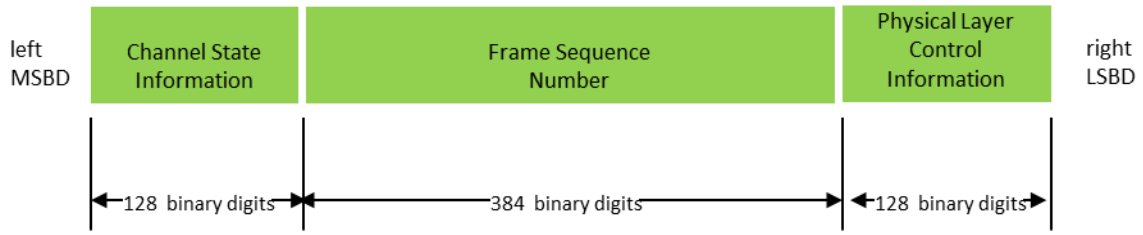

Figure 3-4: Control Data Field

3.1.7.2.1 Channel State Information

Channel state information assists in the decoding process. The quality of the channel is estimated by comparing the received unique word field for a given frame against the set of known unique words that could be present on that link. The correlation (i.e., number of matching binary digits) between the received unique word field and the correct unique word provides an estimate of the quality of the

channel. Since the correct unique word is not known a priori, the highest two correlation values are placed into the sub-fields.

The correlation values shall be mapped to 4 binary digit channel state values, as shown in Table 4, for the maximum and second maximum correlation values.

Table 4. Channel State Information Value Based on Correlation Results

Number Correlated Greater than or Equal to	Number Correlated Less than or Equal to	Channel State Value
373	384	1111
361	372	1110
349	360	1101
337	348	1100
325	336	1011
313	324	1010
301	312	1001
289	300	1000
277	288	0111
265	276	0110
253	264	0101
241	252	0100
229	240	0011
217	228	0010
205	216	0001
0	204	0000

shows the mapping of the 4 binary digit channel state values to an 8 binary digit input sequence of a (127,8) BCH encoder.

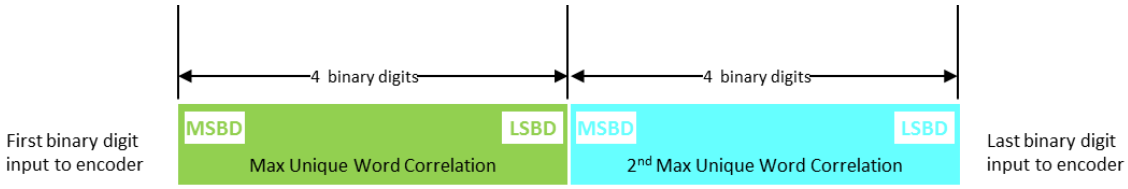

Figure 3-5. Channel State Information Formatting

The output of the BCH encoder is a string of 127 binary digits.

The two 4 binary digit channel state values shall be (127,8) BCH encoded as follows:

1. Let information bits $m = (m_7, m_6, m_5, m_4, m_3, m_2, m_1, m_0)$
2. Multiply the message polynomial $m(x) = m_7x^7 + m_6x^6 + \ldots + m_0$ by x^{119}.
3. Divide $x^{119}m(x)$ by $g(x)$, the generator polynomial. Let $d(x) = d_{118}x^{118} + \ldots + d_0$ be the remainder.
4. Let parity binary digits $d = (d_{118}, \ldots, d_0)$.

The generator polynomial, $g(x)$, for the (127,8) BCH encoder shall be defined as: $g(x) = g_{119}x^{119} + \ldots + g_0$ where the values of g are given in Table 5.

Table 5. (127,8) BCH Generator Polynomial Coefficients

	MSB														
g	g_{119}	g_{118}	g_{117}	g_{116}	g_{115}	g_{114}	g_{113}	g_{112}	g_{111}	g_{110}	g_{109}	g_{108}	g_{107}	g_{106}	g_{105}
binary	1	1	1	0	0	0	1	0	0	1	1	1	0	1	0
g	g_{104}	g_{103}	g_{102}	g_{101}	g_{100}	g_{99}	g_{98}	g_{97}	g_{96}	g_{95}	g_{94}	g_{93}	g_{92}	g_{91}	g_{90}
binary	1	1	0	1	0	0	0	0	0	1	0	1	0	1	0
g	g_{89}	g_{88}	g_{87}	g_{86}	g_{85}	g_{84}	g_{83}	g_{82}	g_{81}	g_{80}	g_{79}	g_{78}	g_{77}	g_{76}	g_{75}
binary	1	1	1	1	0	1	0	0	1	0	0	0	0	1	1
g	g_{74}	g_{73}	g_{72}	g_{71}	g_{70}	g_{69}	g_{68}	g_{67}	g_{66}	g_{65}	g_{64}	g_{63}	g_{62}	g_{61}	g_{60}
binary	0	0	0	1	1	0	1	0	1	0	0	1	1	0	0
g	g_{59}	g_{58}	g_{57}	g_{56}	g_{55}	g_{54}	g_{53}	g_{52}	g_{51}	g_{50}	g_{49}	g_{48}	g_{47}	g_{46}	g_{45}
binary	1	1	1	1	1	0	0	1	0	0	1	0	1	0	0
g	g_{44}	g_{43}	g_{42}	g_{41}	g_{40}	g_{39}	g_{38}	g_{37}	g_{36}	g_{35}	g_{34}	g_{33}	g_{32}	g_{31}	g_{30}
binary	0	1	0	1	1	1	0	0	1	1	0	1	1	1	0
g	g_{29}	g_{28}	g_{27}	g_{26}	g_{25}	g_{24}	g_{23}	g_{22}	g_{21}	g_{20}	g_{19}	g_{18}	g_{17}	g_{16}	g_{15}
binary	1	1	1	1	1	1	0	1	1	0	1	1	0	0	1
g	g_{14}	g_{13}	g_{12}	g_{11}	g_{10}	g_9	g_8	g_7	g_6	g_5	g_4	g_3	g_2	g_1	g_0
binary	0	1	1	0	0	0	0	1	0	0	0	1	1	1	1
															LSB

The 128 binary digit channel state information field of the physical frame header shall be composed of the following subfields (from MSBD to LSBD) as shown in :

- Reserved (or spare), 1 binary digit with a value of 0
- Channel State parity bits, 119 binary digits
- Max Correlation Channel State Value, 4 binary digits
- 2nd Max Correlation Channel State Value, 4 binary digits

Sub-Field	Res	Channel State parity binary digits			Max Correlation Channel State Value				2nd Max Correlation Channel State Value			
BCH Order	N/A	d_{118}	…	d_0	m_7	m_6	m_5	m_4	$\mathbf{m_3}$	m_2	m_1	m_0
Bit	0	1	…	119	120	121	122	123	124	125	126	127
	MSBD											LSBD

Figure 3-6. Channel State Information Field

The content of the channel state information field is either reserved or contains channel state information, depending on the link. For example, a Space Relay computes the channel state information for the link from a User terminal and uses this information to populate the channel state information field of the physical layer frame header for the link to a Ground Relay as described above.

When the channel state information field is reserved (i.e., not used), it shall be set to all zeros.

Channel state information fields shall be populated at the different interfaces as shown in Table 6.

Table 6. Channel State Information Field Values

Interface	Return Data Frames	Space Relay Telemetry Frames	Return Fill Frames	Forward Data Frames	Space Relay Command Frames	Forward Fill Frames
User Terminal – Space Relay	Max = 1111 2nd Max = 0000	N/A	Max = 1111 2nd Max = 0000	Values computed from Ground Relay – Space Relay uplink	N/A	Max = 1111 2nd Max = 0000
Space Relay – Ground Relay	Values computed from User-Space Relay uplink	Max = 1111 2nd Max = 0000	Max = 1111 2nd Max = 0000	Reserved or Max = 1111 2nd Max = 0000	Max = 1111 2nd Max = 0000	Max = 1111 2nd Max = 0000
Others TBS						

3.1.7.2.2 Frame Sequence Number

The frame sequence number (FSN) field of the physical layer frame header is a BCH encoded value that conveys the 22 binary digit FSN, which is incremented at the user source and used at the de-interleaver to identify frame gaps for proper de-interleaving. Note that frame gaps may occur during fades or dropouts that are sufficiently long that more than one fill frame may have been lost, making the next expected FSN ambiguous.

For each successive frame that is formed for each data stream, the FSN shall be incremented by 1. When the FSN reaches the maximum value of 2^{22}-1, it rolls over to 0 at the next increment.

At the interface between two Space Relay terminals on the same satellite, the frame sequence numbers for frames with the same unique word shall be monotonically increasing, with the exception of rollover transition.

The 22 binary digit FSN is provided as an input to a (127,22) BCH encoder as shown in . The format of the BCH encoder output is shown in . The output of the BCH encoder is then replicated three times to populate the FSN field of the physical layer frame header.

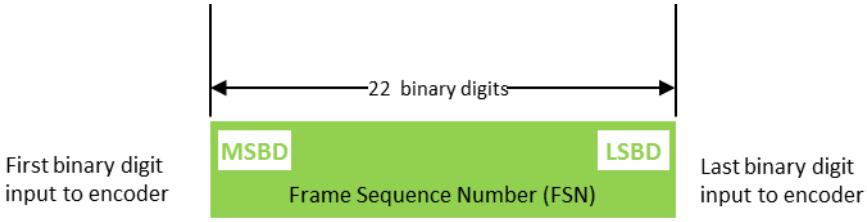

Figure 3-7. Format of Frame Sequence Number Input to BCH Encoder

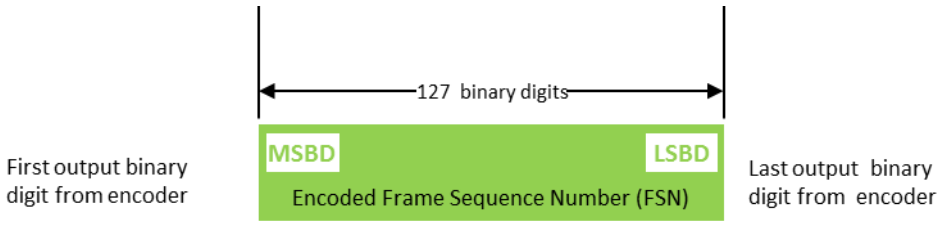

Figure 3-8. Encoded FSN Formatting

The 22 binary digit frame sequence number shall be (127,22) BCH encoded as follows:

1. Let information bits $m = (m_{21}, m_{20}, \ldots, m_0)$
2. Multiply the message polynomial $m(x) = m_{21}x^{21} + m_{20}x^{20} + \ldots + m_0$ by x^{105}.
3. Divide $x^{105}m(x)$ by $g(x)$, the generator polynomial. Let $d(x) = d_{104}x^{104} + \ldots + d_0$ be the remainder.
4. Let parity binary digits $d = (d_{104}, \ldots, d_0)$.

The generator polynomial, $g(x)$, for the (127,22) BCH encoder shall be defined as: $g(x) = g_{105}x^{105} + \ldots + g_0$ where the values of g are given in Table 7.

Table 7. (127,22) BCH Generator Polynomial Coefficients

	MSB															
g	g_{105}	g_{104}	g_{103}	g_{102}	g_{101}	g_{100}	g_{99}	g_{98}	g_{97}	g_{96}	g_{95}	g_{94}	g_{93}	g_{92}	g_{91}	
binary	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	
g	g_{90}	g_{89}	g_{88}	g_{87}	g_{86}	g_{85}	g_{84}	g_{83}	g_{82}	g_{81}	g_{80}	g_{79}	g_{78}	g_{77}	g_{76}	
binary	0	0	0	0	1	1	1	0	0	0	1	0	0	0	0	
g	g_{75}	g_{74}	g_{73}	g_{72}	g_{71}	g_{70}	g_{69}	g_{68}	g_{67}	g_{66}	g_{65}	g_{64}	g_{63}	g_{62}	g_{61}	
binary	0	1	0	0	1	1	1	0	1	0	0	1	0	1	0	
g	g_{60}	g_{59}	g_{58}	g_{57}	g_{56}	g_{55}	g_{54}	g_{53}	g_{52}	g_{51}	g_{50}	g_{49}	g_{48}	g_{47}	g_{46}	
binary	1	0	1	0	0	1	0	1	0	0	0	1	1	1	0	
g	g_{45}	g_{44}	g_{43}	g_{42}	g_{41}	g_{40}	g_{39}	g_{38}	g_{37}	g_{36}	g_{35}	g_{34}	g_{33}	g_{32}	g_{31}	
binary	1	1	0	0	1	0	0	1	0	1	1	1	0	0	1	
g	g_{30}	g_{29}	g_{28}	g_{27}	g_{26}	g_{25}	g_{24}	g_{23}	g_{22}	g_{21}	g_{20}	g_{19}	g_{18}	g_{17}	g_{16}	
binary	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	
g	g_{15}	g_{14}	g_{13}	g_{12}	g_{11}	g_{10}	g_9	g_8	g_7	g_6	g_5	g_4	g_3	g_2	g_1	g_0
binary	0	1	0	0	1	1	1	0	0	0	1	0	0	0	1	1
																LSB

The BCH encoded frame sequence number shall be repeated three times in the frame sequence number field of the physical frame header.

The 384 binary digit frame sequence number field of the physical frame header shall be composed of the following subfields (from MSBD to LSBD) as shown in :

- Reserved (or spare), 1 binary digit with a value of 0
- FSN parity binary digits, 105 binary digits
- FSN, 22 binary digits
- Reserved (or spare), 1 binary digit with a value of 0
- FSN parity binary digits, 105 binary digits
- FSN, 22 binary digits
- Reserved (or spare), 1 binary digit with a value of 0
- FSN parity binary digits, 105 binary digits
- FSN, 22 binary digits

Sub-Field	Res	FSN parity binary digits			FSN			Res	FSN parity binary digits			FSN			Res	FSN parity binary digits			FSN		
BCH Order	N/A	d_{104}	…	d_0	m_{21}	…	m_0	N/A	d_{104}	…	d_0	m_{21}	…	m_0	N/A	d_{104}	…	d_0	m_{21}	…	m_0
Binary digits	0	1	…	105	106	…	127	128	129	…	233	234	…	255	256	257	---	361	362	…	383
MSBD																		LSBD			

Figure 3-9. Frame Sequence Number Field

If the FSN is required to be corrected and updated, the following steps shall be followed:

1. Triple mode redundancy (TMR) error correction will be applied to the FSN parity binary digits and FSN binary digits by binary-digit-wise majority vote on the three copies contained in the FSN field of the physical frame header.
2. The resulting single copy of the FSN parity binary digits and FSN binary digits will be decoded.
3. If decoding is successful, the triple mode redundant sets of FSN parity binary digits and FSN binary digits in the frame sequence number field of the physical layer frame header will be updated with the decoded FSN parity binary digits and FSN binary digits computed in Step 2.
4. If decoding is unsuccessful, the triple mode redundant sets of FSN parity binary digits and FSN binary digits in the frame sequence number field of the physical layer frame header will be updated with the TMR error corrected FSN field computed in Step 1.

Note: If the FSN is not required to be corrected or updated, then the steps above may still be followed. The intent is to allow receivers to correct and update the FSN of all data frames, including frames that do not require FSN corrections or updates.

3.1.7.2.3 Physical Layer Control Information

3.1.7.2.3.1 Physical Layer Control Field

The physical layer control field provides a reliable, low-rate bi-directional communication channel between two terminals over the optical link. This channel transports messages with acknowledgements. The purpose of the channel is to support end-to-end feedback loops involving the cooperation of both terminals. One specific type of end-to-end feedback loop is closed-loop point-ahead (CLPA), which is described in Section 3.1.7.2.3.2.

Note: Implementation and support of intermediate layers, e.g. link layer, transport layer, etc. between the physical layer control and application layers, to support robust and reliable messaging services over the physical layer control channel are tasks that are internal to the terminals. These functions do not concern the specification of the interface between the terminals, and are therefore beyond the scope of this standard.

Any information conveyed on the physical layer control channel is generated locally by the terminal.

The physical layer control information is represented in the physical layer frame header of each physical layer frame by a BCH(127, 22) codeword as described below.

Physical layer control channel information shall be (127,22) BCH encoded as follows:

1. Let information bits $m = (m_{21}, m_{20}, \ldots, m_0)$
2. Multiply the message polynomial $m(x) = m_{21}x^{21} + m_{20}x^{20} + \ldots + m_0$ by x^{105}.
3. Divide $x^{105}m(x)$ by $g(x)$, the generator polynomial. Let $d(x) = d_{104}x^{104} + \ldots + d_0$ be the remainder.
4. Let parity binary digits $d = (d_{104}, \ldots, d_0)$.

The format for the binary digits input to the BCH encoder are the same as for the FSN as shown in . The 22 binary digit representation of these measurements is (**TBS**).

The generator polynomial, g(x), for the (127,22) BCH encoder shall be defined as: $g(x) = g_{105}x^{105} + \ldots + g_0$ where the values of g are given in Table 7.

The 128-binary digit physical layer control information field of the physical frame header shall be composed of the following subfields (from MSBD to LSBD) as shown in :

- Reserved (or spare), 1 binary digit with a value of 0
- Physical layer control parity bits, 105 binary digits
- Physical layer control information, 22 binary digits

Sub-Field	Res	Physical Layer Control parity binary digits			Physical Layer Control Information		
BCH Order	N/A	d_{104}	…	d_0	m_{21}	…	m_0
Binary digits	0	1	…	105	106	…	127
	MSBD						LSBD

Figure 3-10. Physical Layer Control Information Field

The content of the physical layer control information field is either reserved or contains physical layer control information, depending on the link.

When the physical layer control information field is reserved (i.e., not used), it shall be set to all zeros.

Physical layer control information fields shall be populated at the different interfaces as shown in Table 8.

Table 8. Physical Layer Control Information Field Values

Interface	Return Data Frames	Space Relay Telemetry Frames	Return Fill Frames	Forward Data Frames	Space Relay Command Frames	Forward Fill Frames
User Terminal – Relay Terminal	Values computed for return data link	N/A	Values computed for return data link	Values computed for forward data link	N/A	Values computed for forward data link
Space Relay – Ground Relay	Don't Care	Don't Care	Reserved	Reserved	Reserved	Reserved
Other TBS						

The 22 binary digits of physical layer control information shall be composed of the following subfields (from MSBD to LSBD), as shown in :

1. Link state binary digit (for frame synchronization status), 1 binary digit
2. Field repetition count, 5 binary digits
3. Control binary digit, 1 binary digit
4. Message octet number, 4 binary digits
5. Reserved (or spare), 3 binary digits with a value of '0'
6. Data octet, 8 binary digits

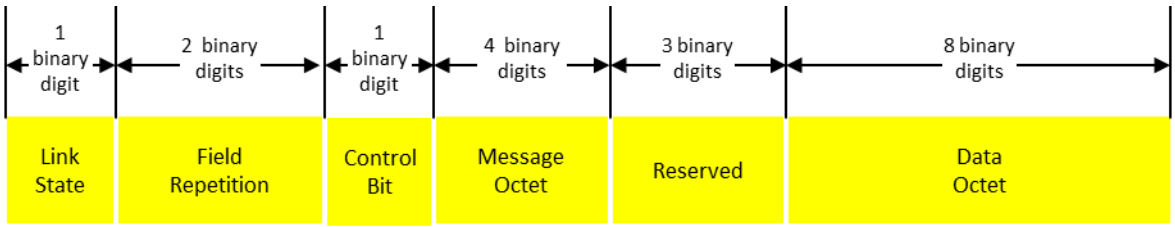

Figure 3-11. Physical Layer Control Information

The link state binary digit shall be set to '1' on transmitted frames when frame synchronization of received frames is achieved.

The link state binary digit is checked on received frames to determine whether the other end of the link has achieved synchronization. When a '1' is measured on the link state bit of received frames, both sides can be assumed to have achieved frame synchronization.

If there is no valid data to send, then the following fields shall be set to all '0's:

1. Field repetition count
2. Control binary digit
3. Message octet number
4. Data octet

If there is valid data to send, then the control binary digit shall be set to '1' for 32x*N*x*L* sequential frames, where *N* varies by data rate and is provided in Table 9, and *L* is the length of the message in octets.

Table 9. *N*-Repetition Values

Data Rate (Mbps)	*N*-Repetition
1244	40
622	20
311	10
155	5
51.8	2
16	1
8	1
4	1
2	1

In the following text, the 32x*N*x*L* frames comprising a message will be numbered 0 through 32x*N*x*L*-1, and the *L* octets ill be numbered 0 through *L*-1.

The field repetition count field for frame *n* of a message shall be set to *f*[*n*], where:

$$f[n] = floor(n/N)\text{mod}32$$

Note: Here *floor*(*x*) represents the floor function, i.e., *floor*(*x*) is the largest integer not greater than *x*. The field repetition count starts at 0, increments every *N* frames, and wraps around from 31 back to 0. This repetition, which varies according to data rate, ensures that every byte experiences approximately the same duration in time of the fading channel at each of the various data rates.

The message byte number field for frame *n* of a message shall be set to *m*[*n*], where:

$$m[n] = n \text{ mod}(32N).$$

Note: The message byte number starts at 0 and increments every 32*N* frames.

The data byte field for frame *n* shall be set to the $m[n]^{th}$ byte of the message, where $m[n]$ is defined as above.

Note: The first 32*N* frames contain the first octet of the message. The next 32*N* frames contain the second octet, etc.

The physical layer control information is encoded for each outgoing frame and is decoded for each incoming frame. The BCH(127, 22) decoder should provide indication of whether a codeword was decoded successfully or not. The terminals should each provide a mechanism to take advantage of the BCH forward error correction, the link state binary digit, and the field repetition count to recover the data octet and the overhead binary digits (control binary digit and message octet number) from each field repetition period.

The link state binary digit may change value on a frame-by-frame basis without regard for the field repetition count. The link state binary digit's value is considered valid for each correctly decoded BCH(127,22) codeword corresponding to the physical layer control field.

The physical layer control field may be used intermittently. When a terminal has nothing to send, the control binary digit is set to '0' to indicate that the data byte does not contain valid data.

Data octets are organized into physical layer control messages. Message lengths range from 5 octets to 16 octets. The message octet number field indicates the data octet's position in the current message.

The length of physical layer control messages shall be between 5 octets and 16 octets, inclusive.

The physical layer control message shall contain the following fields (from MSBD to LSBD), as shown in :

1. Octet 0
   - Preamble, 4 binary digits
   - Message length, 4 binary digits
2. Octet 1 and 2
   - Message number, 16 binary digits
3. Octet 3 through *L*-2
   - Message data, 1 - 11 binary digits
4. Octet *L*-1
   - CRC, 8 binary digits

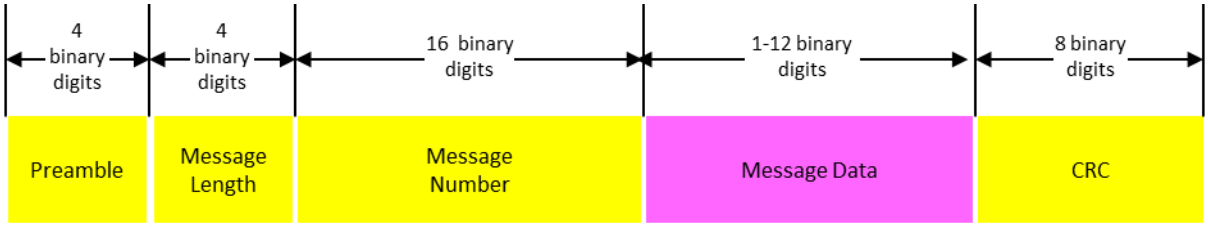

Figure 3-12. Physical Layer Control Message Format

The preamble field of the physical layer control message shall be "1010".

The message length field of the physical layer control message shall be set to *L*, the length of the message in bytes.

Note: The length of the message includes the preamble, message length, message number, and CRC fields.

The CRC of the physical layer control message shall be determined by the CRC-8-CCITT algorithm with a generating polynomial of $1 + x + x^2 + x^8$.

Physical layer control messages that do not pass CRC check shall be discarded.

The message number shall be incremented by one for each new message.

Note: The message number is used in acknowledgements to acknowledge received messages.

A terminal shall send an acknowledgement message for each received physical layer control message that is not itself an acknowledgement message.

If either the transmitted or received link state binary digit is '0', then the message layer shall reset until both link state binary digits are set to '1'.

Note: Resetting the message layer involves the following steps:

1. Flushing the queue of physical layer control messages to be transmitted
2. Flushing the queue of physical layer control messages waiting to be acknowledged
3. Not transmitting any physical layer control messages

Physical layer control message types shall be one of the types shown in Table 10.

Note: A set of message types is reserved for future use.

Table 10. Messages supported by the physical layer control field

Message Type	Message Data Length (octets)	Message Data Description
Message acknowledgment	3	Opcode 0x00; Acknowledged message number (high octet, low octet)
Closed-loop point-ahead	12	Opcode 0x01; Second octet is CLPA message
Reserved for future use	1-11	Opcode 0x03
Reserved for future use	1-11	Opcode 0x04
Reserved for future use	1-11	Opcode 0x05

When the message type is *message acknowledgement*, the message data field shall be three (3) octets long.

When the message type is *message acknowledgement*, the first octet (octet 0) of the message data field shall be set to the message acknowledgment opcode 0x00.

When the message type is *message acknowledgement*, the second and third octets (octets 1 and 2) of the message data field shall be set to the high and low octet, respectively, of the message number being acknowledged.

When the message type is *closed-loop point-ahead*, the message data field shall be two (2) octets long.

When the message type is *closed-loop point-ahead*, the first octet (octet 0) of the message data field shall be set to the closed-loop point-ahead opcode 0x01.

When the message type is *closed-loop point-ahead*, the message second octet (octet 1) of the message data field shall be one (1) octet long set to the CLPA message to be transmitted.

Note: CLPA messages are defined in Section 3.1.7.2.3.2 where the 3 binary digit values shown in Table 11 represent the 3 LSBDs of the CLPA message and the 5 MSBDs of the CLPA message are all set to ‘0'.

The terminal shall maintain a list of physical layer control message numbers that it has sent but that have not yet been acknowledged.

Each physical layer control message number is allowed to remain on this list for **TBD** seconds, after which the message shall be removed from the list.

When an unacknowledged physical layer control message is removed from the list because of timeout, the message shall be re-transmitted as a new message with a new message number unless it is no longer relevant.

3.1.7.2.3.2 Closed-Loop Point-Ahead Protocol

In the description below, the closed-loop point-ahead (CLPA) process is defined using MEASURER/ADJUSTER nomenclature. The terminal that is adjusting its pointing angle is referred to as the ADJUSTER. The terminal that is measuring the received signal and providing feedback to the ADJUSTER is referred to as the MEASURER. For the example shown in , the User Terminal is the ADJUSTER and the Space Relay terminal is the MEASURER.

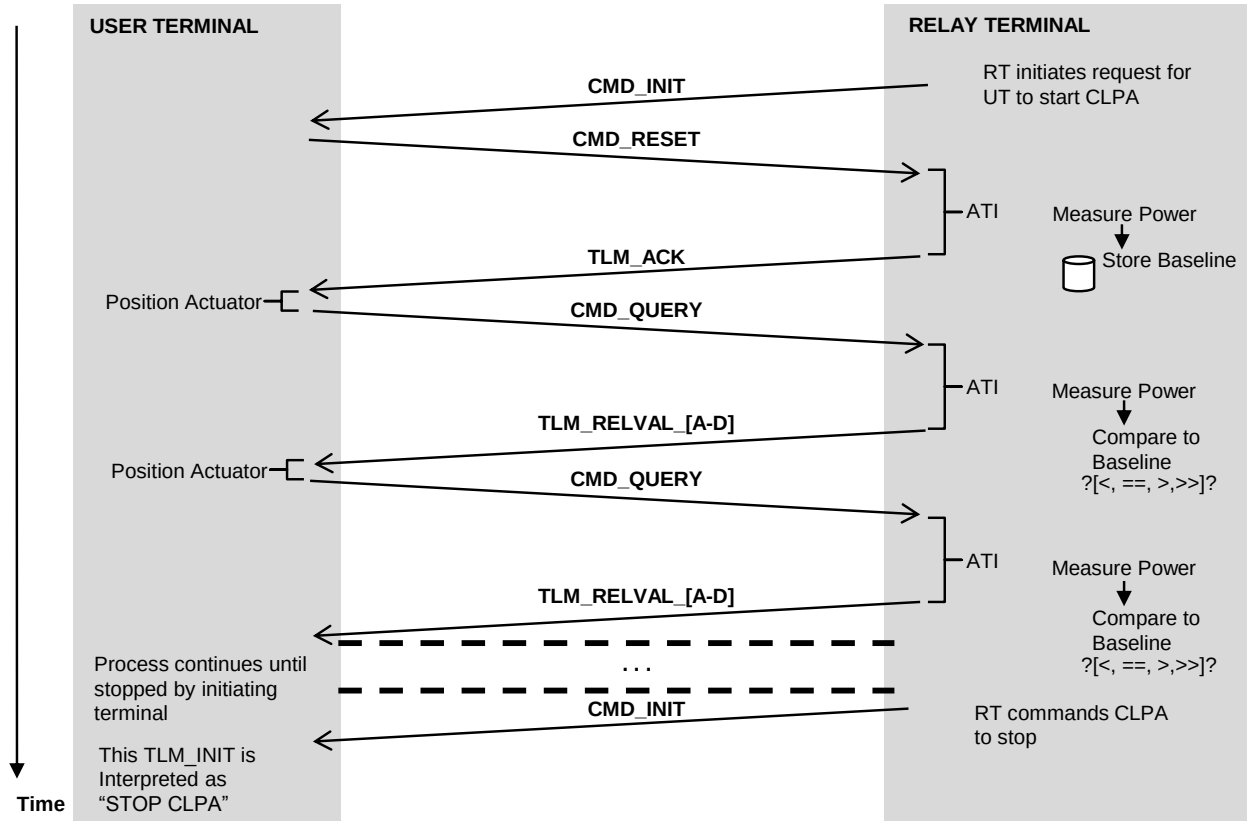

Figure 3-13. Example of an exchange of messages to enable a User Terminal to correct its pointing based on feedback from a Space Relay Terminal.

Table 11. CLPA Message Content

MSG NO	BINARY VALUE	NAME	DESCRIPTION	CONDITION	ACTION	REQ'D REPLY MSG

0	000b	CMD_INIT	Request to initialize CLPA. (*MEASURER* sends to *ADJUSTER*)	If *ADJUSTER* accepts request to start CLPA session:	Send Reply Msg	CMD_RESET
				If *ADJUSTER* denies request to start CLPA session:	Send Reply Msg	CMD_QUERY (overloaded)
				If *ADJUSTER* receives CMD_INIT while CLPA session is active:	STOP CLPA session	(none)
1	001b	CMD_RESET	Request to initialize CLPA and Initiate baseline measurement (*ADJUSTER* sends to *MEASURER*)	If *MEASURER* accepts request to start CLPA:	1. Record baseline power measurement 2. Send Reply Msg	TLM_ACK
				If *MEASURERER* denies request to start CLPA:	Send Reply Msg	CMD_INIT (overloaded)
2	010b	CMD_QUERY	Initiates a relative value measurement (*ADJUSTER* sends to *MEASURER*)	Default response:	1. Record power measurement 2. Compare with baseline 3. Send Reply Msg	TLM_RELVAL _[A-D], according to relative power value
				If CMD_QUERY is received immediately after CMD_INIT is sent:	STOP CLPA session	(none)
3	011b	TLM_ACK	Indicates baseline measurement is complete (*MEASURER* sends to *ADJUSTER*)			
4	100b	TLM_RELVAL_A	Value is more than 0.1 dB below baseline (*MEASURER* sends to *ADJUSTER*)			

5	101b	TLM_ RELVAL_B	Value is within +/- 0.1 dB of baseline (*MEASURER* sends to *ADJUSTER*)			
6	110b	TLM_ RELVAL_C	Value is 0.1 dB to 0.3 dB above baseline (*MEASURER* sends to *ADJUSTER*)			
7	111b	TLM_ RELVAL_D	Value is more than 0.3 dB greater than baseline (*MEASURER* sends to *ADJUSTER*)			

All terminals shall have the capability to simultaneously act as either a MEASURER or an ADJUSTER.

All terminals shall have the capability to generate CLPA messages as defined in Table 11.

The response of a terminal acting as either a MEASURER or ADJUSTER to a CLPA message shall be consistent with Table 11.

A terminal shall respond to messages from the remote terminal when required, as defined in Table 11, within 10 seconds (**TBR**).

Note: The messages requiring a timely response are those with a "required reply message" shown in the far right column of Table QWE. Also, the specified response time is measured from receipt of the message to transmission of the response on the physical layer control channel, and is chosen to be slightly greater than the averaging time interval (ATI) limit to account for processing and propagation times.

A terminal shall have the capability to send and receive CLPA messages at a rate of at least 1 CLPA message per second.

A terminal shall have a means of measuring the received signal strength over an averaging time interval (ATI).

Note 1: The specific metric used to measure the strength of the received signal must be based on received power. Additionally, a terminal must correlate this measurement such that it is consistent with the relative variations in received optical power as specified by the definitions of the CLPA messages in Table 11.

Note 2: The averaging time interval (ATI) is defined as the time interval over which the average received power is measured.

Note 3: The ATI duration must be chosen to be sufficiently long so as to average out any received power fluctuations that are due to residual pointing jitter, as well as the fading channel..

The averaging time interval (ATI) shall be less than 8 seconds (**TBR**).

Note: The intent of the upper limit on ATI is to ensure proper interaction between terminals using the CLPA process, e.g., to ensure timely responses or to prevent unintended timeouts from occurring within either terminal.

A terminal acting as the ADJUSTER shall have a means of adding a bias to the outgoing beam to null pointing errors for the purpose of maximizing the power delivered to the remote terminal.

The bias shall be computed based on the CLPA feedback.

Note: There is no requirement on the specific algorithm employed for adjusting the pointing bias based on the TLM_RELVAL_[A-D] messages. For example, a hill-climbing algorithm can be used.

A terminal acting as the MEASURER shall be capable of measuring changes in the received power with sufficient accuracy to support the TLM_RELVAL_[A-D] response messages shown in Table 11.

3.1.8 FRAME SCHEDULE

Terminals use fixed schedules when transmitting frames.

User Terminal transmitters and Ground Relay transmitters shall use one of the physical layer frame schedules in Table 3-12.

Table 3-12. Physical Layer Frame Schedules

Terminal	Data Rate	Schedule

User Terminal	51.8 – 1244 Mbps	Repeat Forever {
		9 x Data Frames
		1 x Fill Frame
		}

User Terminal	2-16 Mbps	Repeat Forever { 14 x Data Frames

		1 x Fill Frame }

Ground Relay	51.8 – 1244 Mbps	Repeat Forever {
		9 x Data Frames
		1 x Fill Frame
		}

Ground Relay	2-16 Mbps	Repeat Forever {
		14 x Data Frames
		1 x Fill Frame
		}

Space Relay	**TBS**	**TBS**

The spacing between data frames of the same stream, at the input to a User Terminal or Ground Relay, shall not exceed three frame periods, under error-free conditions. This maximum data frame spacing accounts for physical layer fill frames and jitter introduced at the Space Relay.

The difference between the actual received data frame rate and nominal transmitted data frame rate, at a User Terminal or Ground Relay, shall differ by no more than +/- 50 ppm. This maximum frame rate skew accounts for clock accuracy and Doppler. Nominal data frame rates are shown in Table 3-13.

Table 3-13. Nominal Data Frame Rates

Data Mode	Nominal Data Frame Rate (fps, rounded)
U-1244	39,378
U-622	19,689
U-311	9,844
U-155	4,922
U-51.8	1,641
U-16	1,021
U-8	1,021
U-4	1,021
U-2	1,021

3.1.9 RANDOMIZER

To prevent deleterious effects related to run length, the optical link signals must have sufficient binary digit-timing content at the optical waveform interface. A suitable binary digit pattern, which prevents a long sequence of '1's or '0's, is provided by a randomizer.

On transmission, randomization is performed prior to burst-mode formatting (if present) and DPSK encoding. On reception, descrambling is performed following frame synchronization and removal of off-times (if present) from the data stream.

The terminal shall perform randomization on the signal it transmits onto the optical link.

The terminal shall perform frame alignment and descrambling on the signal it receives from the optical link.

The operation of the optical link randomizer shall be functionally identical to that of a frame synchronous scrambler of sequence length 65,535 operating at the frame rate.

Both data frames and fill frames (if present) on the optical link shall be randomized.

The optical link randomizer shall be the equivalent of a linear feedback shift register (LFSR) with a pattern length of 216 – 1.

The generating polynomial of the optical link randomizer shall be $1 + x + x^3 + x^{12} + x^{16}$.

Figure 3-14 shows a functional diagram of the frame-synchronous optical link scrambler. Note that this figure represents an example implementation for illustration purposes. Alternate implementations that perform the identical function are acceptable.

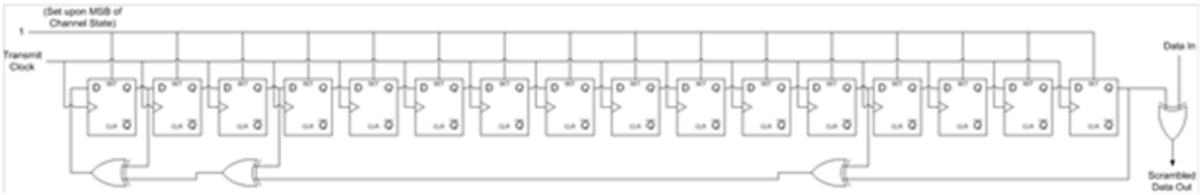

Figure 3-14. 216 – 1 LFSR Optical Link Scrambler

The unique word field (frame alignment signal) of the physical layer frame header shall not be randomized.

The optical link randomizer shall be set to 0xFFFF on the most significant bit of the channel state information field, which follows the last bit of the unique word field (frame alignment signal) of the physical layer frame.

The most significant bit of the channel state information field of the physical layer frame, and all subsequent bits to be randomized, shall be added modulo 2 to the output from the x16 position of the optical link randomizer.

The optical link randomizer shall run continuously beginning with the most significant bit of the channel state information field through the remainder of the physical layer frame.

All 64800 frame data bits of any fill frame to be transmitted on an optical link shall be set to ‘0’ before scrambling.

3.2 TERMINAL B

3.2.1 FRAME STRUCTURE

3.2.2 FRAME SYNCHRONIZATION MARKER

3.2.3 SLICER

3.2.4 CHANNEL CODING

3.2.5 CHANNEL INTERLEAVING

3.2.6 MAPPER (SYMBOL TO CHANNEL SYMBOL)

4 RANGING

ANNEX A

[ANNEX TITLE]

[EITHER NORMATIVE OR INFORMATIVE]

[Annexes contain ancillary information. Normative annexes precede informative annexes. Informative references are placed in an informative annex. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for discussion of the kinds of material contained in annexes.]

ANNEX B

SECURITY

(INFORMATIVE)

B1 INTRODUCTION

B2 SECURITY CONCERNS WITH RESPECT TO THE CCSDS DOCUMENT

B2.1 DATA PRIVACY

B2.2 DATA INTEGRITY

B2.3 AUTHENTICATION OF COMMUNICATING ENTITIES

B2.4 CONTROL OF ACCESS TO RESOURCES

B2.5 AVAILABILITY OF RESOURCES

B2.6 AUDITING OF RESOURCE USAGE

B3 POTENTIAL THREATS AND ATTACK SCENARIOS

B4 CONSEQUENCES OF NOT APPLYING SECURITY TO THE TECHNOLOGY