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Space Development Agency
Optical Intersatellite Link (OISL) Standard

Version 2.1.2

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June 5, 2020	NA	Draft as issued for Transport Layer T0 RFP HQ085020R0001
June 5, 2020	1.0	Editorial changes only
Feb 5, 2021	2.0	Final version
October 15, 2021	2.1	This version incorporates errors, omissions, and clarifying information in support of Tranche 0.
November 24, 2021	2.1.1	DRAFT Patch update - Provided clarifying information and incorporated fixes for errata
December 13, 2021	2.1.2	Updated Patch version based on comments received on DRAFT 2.1.1 patch

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1 Introduction

The Optical Intersatellite Link (OISL) standard establishes the interoperability requirements for all Optical Links that wish to communicate with the Space Development Agency (SDA) Tranche 0 system, including space-to-space and space-to-ground links.

1.1 Purpose and Scope

The purpose of this document is to define an interface specification for space-to-space and space-to-ground optical communications for SDA Tranche 0. The scope of this document is limited to the physical and data link layers of the optical communication links.

1.2 Assumptions

The development of this standard has focused on the optical communications requirements to be demonstrated in the SDA Tranche 0 (T0) constellation.

The following items set this document's scope:

1. Only spacecraft in Low Earth Orbit (LEO) are part of the T0 constellation. Interoperability with spacecraft in other orbital regimes is not in scope.
    a. Three Classes of Links have been assumed
        i. In-Plane
        ii. Cross-Plane
        iii. Space-to-Terrestrial
2. The later (T1+) constellation OISLs are not required to be backward compatible with the T0 system. This document is applicable to the SDA T0 Constellation.
3. The optical link ranges in T0 will span from a nearest allowable distance to a maximum of 6500 km.
    a. No analysis of the implications of this interface specification has been performed on links beyond 6500 km
    b. The nearest allowable distance is the minimum safe operating distance, with appropriate margin, for which the transmitter is capable of delivering a signal to the remote receiver below its safe irradiance limit
4. The OISL terminals:
    a. Operate in the Optical C-Band
    b. Operate between 100 Mbps and 1 Gbps data rates with nominal operations at 312.5 Mbps
    c. Employ direct detection optical receivers
5. While this document does not levy requirements on size, weight, power, and cost (SWAP-C), the SDA T0 spacecraft and optical terminal SWAP-C and mission CONOPS have influenced the range, data rate, and other assumptions and decisions contained herein.

1.3 Nomenclature and Definitions

1.3.1 **Normative Text**

The following conventions apply for the normative specifications in this Specification:

a. the words ‘shall’ and ‘must’ imply a binding and verifiable specification
b. the word ‘should’ implies an optional, but desirable, specification
c. the word ‘may’ implies an optional specification
d. the words ‘is’, ‘are’, and ‘will’ imply statements of fact

1.3.2 **Definitions from the Open Systems Interconnection (OSI) Basic Reference Model**

This standard makes use of a number of terms from the OSI model as defined in [1]. The definitions of those terms in this standard conform to the definitions contained in [1].

2 Standard Definition

2.1 Pointing, Acquisition, and Tracking

2.1.1 PAT Introduction

Acquisition time shall be less than 100 seconds after bus offset calibration. Acquisition time should be less than 10 seconds after bus offset calibration. A transmitted amplitude modulation (AM) tracking tone shall be provided as defined in Section 2.6.2.

The PAT spatial acquisition shall be referred to as a lead and follow strategy (referred to as master-slave in [2]).

The PAT approach below provides the state machine and parameters for a common Pointing, Acquisition and Tracking approach for optical intersatellite links and optical communications terminals (OCTs), generally, employed by the Space Development Agency (SDA) T0 programs. The scope of this PAT approach is limited to Space-to-Space and Space-to-Ground optical connections. Space-to-Space optical connections between terminals produced by the same vendor may offer, in addition to the PAT approach defined herein, additional PAT modes selectable upon command by the ground.

The details below clarify the framework described in Section 2.3 of [2] and provide details not otherwise provided in [2] necessary to ensure PAT interoperability between multiple vendors. This PAT approach employs a lead/follow strategy with time-constrained state changes and synchronized acquisition/re-acquisition attempt start times to ensure PAT interoperability under large uncertainty cone conditions.

2.1.2 Example Spiral Scan

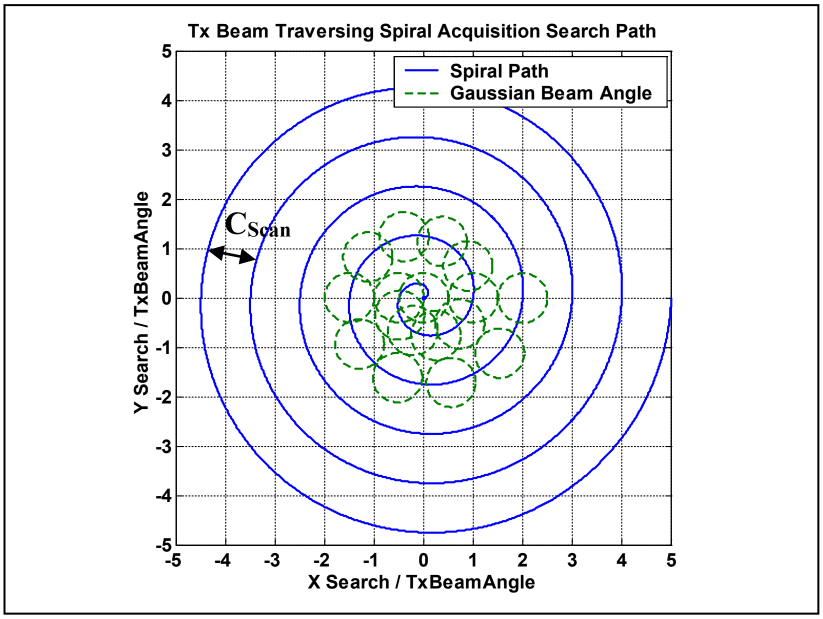

Figure 2-1. Spiral Scan Pattern

Figure 2-1 is the baseline Constant Velocity Archimedes spiral scan approach and is the minimal amount of time necessary for a scan. The spiral scan approach may vary between T0 Optical Vendors, but different scan approaches can increase scan time.

The time to spiral to the search radius C_{Search} is given by the following equation:

$$T_{Scan}^{Spiral} = \pi T_{Scan} \left(\frac{C_{Search}}{C_{Step}} \right)^2$$

The C_{Step} parameter must be selected based on the minimum required receive flux P_{Rx_Min} for the specific OCT. Simplistically, this is illustrated in the following link equation:

$$P_{Tx} - BeamDivergenceLoss - BeamPointingJitterLoss - Margin - OverlapLoss > P_{Rx\_Min}$$

The overlap loss term is related to the ratio of C_{Step} to the transmit beam divergence θ_{TX}. If $C_{Step} = \theta_{TX}$, then the *OverlapLoss* = 8.64 dB. If, on the other hand, $C_{Step} = \theta_{TX}/1.7$ (which is the FWHM diameter), then the *OverlapLoss* = 3 dB, however, the spiral scan will take $1.7^2 = 2.9$x longer.

2.1.3 **T0 Interoperable Pointing, Acquisition, and Tracking**

Modeling the pointing, acquisition, and tracking (PAT) sequence as an event-driven finite-state-machine provides a common model for all T0 OISL Standard Terminals. The purpose of this model is to communicate the current status of the OCT's PAT channel, provide a sequence of events in a geometric construct, and standardize the required parameters.

2.1.3.1 State Machine

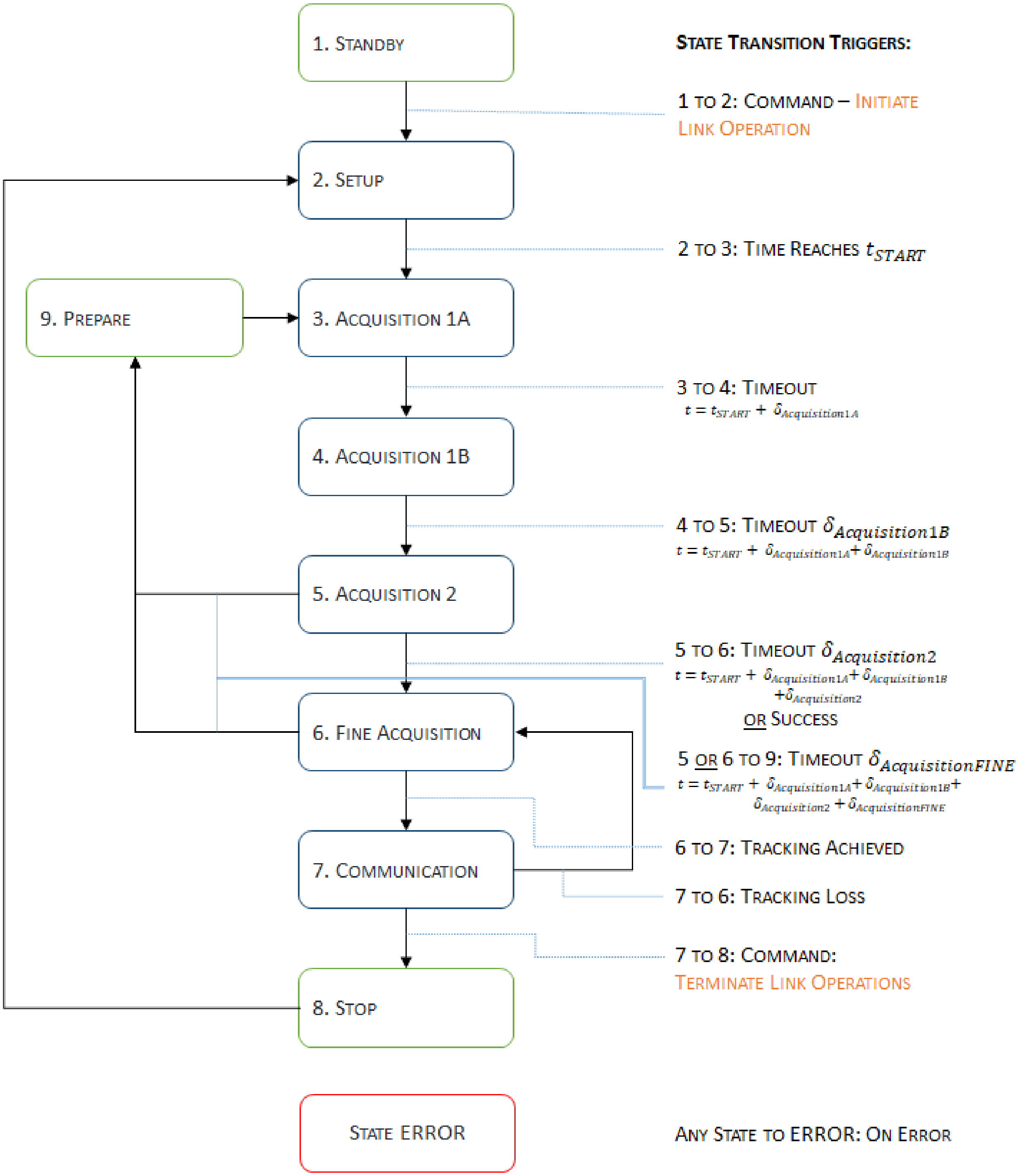

Figure 2-2. T0 Interoperable PAT State Machine

Table 2-1. State Machine Description

ID	Name	Description	Entry Criteria	Exit Criteria
1	**Standby**	OCT waits for further commanding.		Command Received: Initiate Link Operation→Setup
2	**Setup**	After a new link command is received, the OCT is configured according to the link parameters and the coarse pointer starts to move towards the target trajectory.	**Command Received:** Initiate Link Operation	OCT has slewed into position and terminal has been configured ahead of t_{START} being reached Starting time t_{START} is reached →Acquisition Phase 1A
3	**Acquisition Phase 1A**	During acquisition phase 1A the lead OCT scans the starting cone of uncertainty. The follow OCT detects hits and performs pointing adjustments, reducing the level of starting uncertainty.		Configuration Parameter Phase 1A duration reached (δ_{Acq1A}) →Acquisition Phase 1B
4	**Acquisition Phase 1B**	During acquisition phase 1B the follow OCT scans the remaining cone of uncertainty. The lead OCT detects hits and performs pointing adjustments, reducing the level of starting uncertainty.		Configuration Parameter Phase 1B duration reached (δ_{Acq1B}) →Acquisition Phase 2
5	**Acquisition Phase 2**	During acquisition phase 2 either one or both of the two OCT scans the remaining cone of uncertainty. The OCT(s) detects hits and performs pointing adjustments, further reducing the level of uncertainty.		Uncertainty reduced such, that target is within FOV of the fine acquisition sensor (if applicable) →Fine Acquisition Timeout waiting for further hits → Prepare

6	**Fine Acquisition**	During fine acquisition both OCTs are scanning the remaining cone of uncertainty and both OCTs detect hits and perform pointing adjustments to further reduce the level of uncertainty further.		Stable tracking established, continuous receive signal → Communication. Timeout waiting to establish tracking → Prepare
7	**Communication**	Bidirectional data link is established		Command Received: $\delta_{LmtGoStop}$ → Stop Tracking signal lost → Fine Acquisition
8	**Stop**	The link is terminated by command or due to a failure condition. The OCT goes back to standby		Laser and all mechanism stopped and goes back to standby
9	**Prepare**	Prepare for reestablishing the link Complete acquisition sequence is repeated using the configuration according to the latest Initiate Link Command with the next acquisition start time defined by: $T_{nextAcquisitionStart} = t_{START} + \Omega_{AcqPeriod} \cdot ceiling\left[\frac{t - t_{START} + \delta_{AcqPreparation}}{\Omega_{AcqPeriod}}\right]$ where *t* is the current time.	If $\Omega_{AcqPeriod} = 0$, this state is passed through	OCT has slewed into position based on latest ephemeris prediction and terminal configuration and then t_{START} is reached

2.1.3.2 Configuration Parameters and Telemetry

Table 2-2. State Machine Configuration Parameters

Parameter	Parameter Shorthand	Range of Values	Parameter Definition
Start Time	t_{START}		The absolute time at which the PAT sequence begins
Acquisition Type [Optional]	Synchronous or Asynchronous		Synchronous – Start at specified t_{START} Asynchronous – Start immediately [Optional behavior]
Starting Uncertainty Cone (μrad)	TUC	500-vendor FOV	This is the starting cone of uncertainty and is reported as a circular cone radius. This is the search cone. Starting uncertainty may be larger than the system FOV which may require manual intervention
Phase 1A duration (seconds)	δ_{Acq1A}	0-65535	Duration of first spiral scanning phase (1A). Nominally symmetric across terminals, but terminal shall act as commanded.
Phase 1B duration (seconds)	δ_{Acq1B}	0-65535	Duration of second spiral scanning phase (1B). Nominally symmetric across terminals, but terminal shall act as commanded.
Lead or Follow		Lead or Follow	Determines if the terminal shall act as Acquisition Lead or Follow
TX wavelength		A or B	TX wavelength selection
TX Tracking tone modulation		On or off	Determines if TX laser amplitude modulation used
Spiral-Velocity ($u$rad/msec)		0-1000	Spiral velocity compatible with receiver bandwidth of counter terminal. Set per-vendor
Spiral Separation ($u$rad)		0-1000	Spiral velocity compatible with receiver bandwidth of

			counter terminal. Set per-vendor
Phase 2 Maximum Duration (*sec*)	$\delta_{MaxPhase2}$	0-255	Max duration in Acquisition Phase 2 without establishing target is within FOV of the fine acquisition sensor (if applicable)
Fine Acquisition Maximum Duration (seconds)	$\delta_{MaxFine}$	0-255	Max duration in Fine Acquisition without establishing stable tracking
Acquisition Period (seconds)	$\Omega_{AcqPeriod}$	0-65535	Periodicity of acquisition restart times. This is a parameter specified by the ground.
Acquisition Preparation Duration (seconds)	$\delta_{AcqPreparation}$	0-255	The amount of time required for the overall system (comprised of both OISL A and B) to be ready for the next acquisition (which is an exit criteria for the "Prepare" state) is $\delta_{AcqPreparation}$. This is a parameter set by the ground.

Table 2-3. State Machine Telemetry

Parameter	Parameter Shorthand	Parameter Definition
State	S	This is the current state of the top-level state machine.

2.1.4 **Acquisition Scheme**

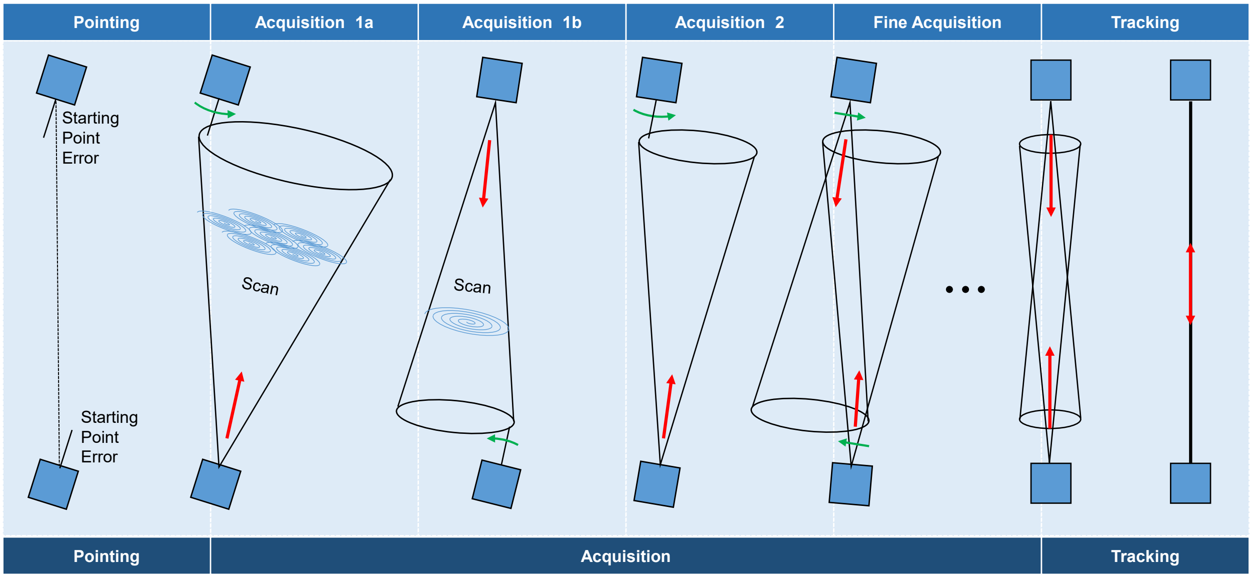

Figure 2-3 PAT Geometric Reference

Figure 2-3 shows the T0 PAT geometric acquisition scheme. The Red arrows denote an active TX beam, the cone around the arrow depicts the size of the uncertainty cone (outer scan radius). Green arrows denote pointing adjustment and reduction of uncertainty cone.

Figure *2-4* provides a notional timeline for each phase and notional uncertainty cone for Phase 1a entry criteria and the transition from Phase 2 to Fine acquisition. Time and uncertainty will be specific for each vendor pairing based on uncertainty determined on orbit after calibration. The leader is on the left column while the follower is on the right column.

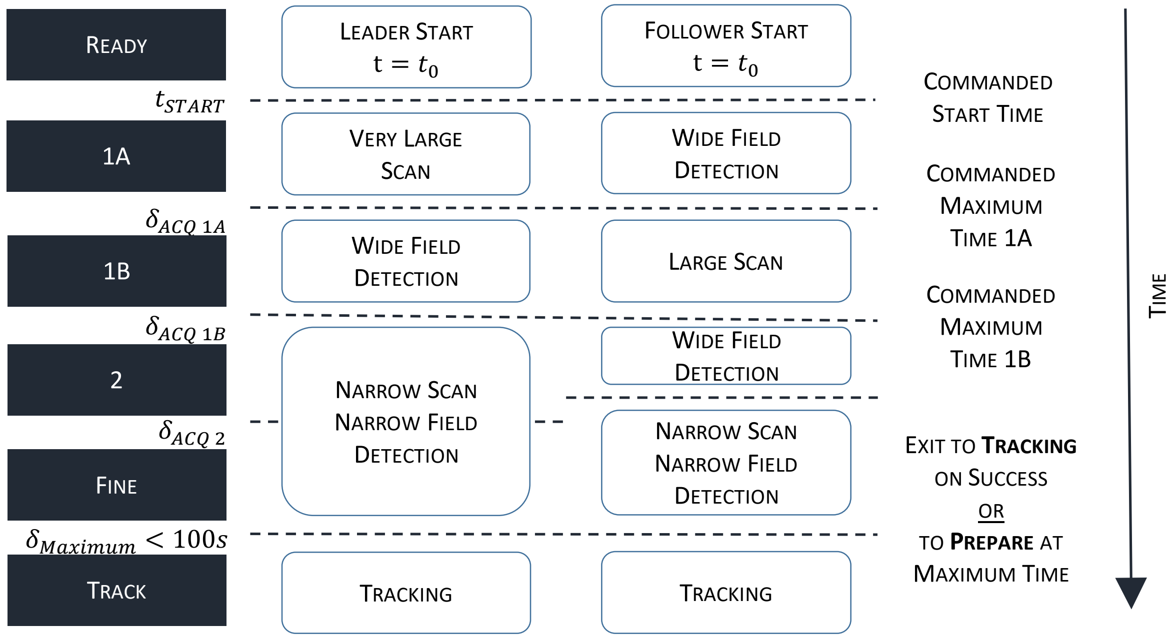

Figure 2-4. PAT Notional OPSCON. Time progresses from top to bottom. The transition from Acquisition 2 to Fine and Fine to Track is triggered by successful tracking. The definition of success for tracking is implementation-dependent. In this diagram, the Leader is depicted as having only a single field size. For this reason, the wide- and narrow-field scan are combined.

2.2 Latency

Latency is defined as the duration of time from arrival of the rising edge of the first bit at the receiver's detector to egress of the complete Ethernet packet from the OISL terminal via the data interface. The T0 data interface is the connection from the OISL modem to the router and typically implemented as a 1 Gbps Ethernet link.

For a given Ethernet packet, the latency is calculated as Egress Time-Ingress Time, where:

- Ingress Time = earliest arrival time of any bit from the packet
- Egress Time = time of egress completion of the entire Ethernet packet

The following latency requirements apply to an Ethernet payload size up to a maximum transmission unit (MTU) of 1500 octets:

- The receive (RX) modem latency shall be less than 15 ms
- The receive (RX) modem latency should be less than 5 ms
- The transmit (TX) modem latency shall be less than 15 ms
- The transmit (TX) modem latency should be less than 5 ms

2.3 Re-Programming

Physical Framing (Section 2.6.3.1), Coding and Scrambling (Section 2.6.3.6 and Section 2.6.3.6.4) and Encapsulation (Section 2.6.3.7) shall be re-programmable on orbit. During reprogramming, the transmission of data may be interrupted.

2.4 Effective Data Rate

The effective data rates for the primary OISL modem frame configurations are summarized in Table 2-4 as a function of the OISL baud rate. The last column of the table indicates the required support for each baud rate.

Table 2-4: Maximum Effective Data Rates for Frame Configurations

Baud Rate (Mbaud)	Frame Duration (microseconds)	Effective Data Rate (Mbps)	Frame Rate (kHz)	Fast Control Channel (Mbps)	Requirement
312.5	79.795	191.290	12.532	0.201	Shall be supported
625	39.898	382.579	25.064	0.401	Should be supported
1250	19.949	765.159	50.128	0.802	Should be supported
2500	9.974	1530.318	100.257	1.604	May be supported
5000	4.987	3060.635	200.513	3.208	May be supported
10000	2.494	6121.270	401.027	6.416	May be supported

Frame duration and frame rate are a function of the frame size defined in Section 2.6.3.1. The effective data rates account for all systematic sources of overhead including preamble, header, CRC's, FEC, and the LPC code. Note that overhead for Ethernet framing is dependent on the distribution of packet sizes and generally does not significantly impact the values in Table 2-4. The maximum data rates tabulated in Table 2-4 are best-case, excluding any retransmissions and assuming an absence of MGMT frames.

2.5 Physical Layer

2.5.1 Channel Definition

Each OISL shall provide an A and B channel operating at the carrier wavelengths as specified in Table 2-5. Center frequency for the channels is defined as $193.1+n\times0.1$ THz, consistent with ITU-T G.694.1 [3].

Table 2-5: Wavelength Channel Definition

Channel	Wavelength	Channel Number
A	1536.61 nm	n = +20
B	1553.33 nm	n = -1

2.5.1.1 Center Frequency Tolerance

The transmitter center frequency shall be accurate to within a tolerance of ± 10 GHz.

2.5.1.2 Laser Line-Width

The modulated laser linewidth shall be less than 10 GHz, measured at full width at half-maximum (FWHM) over a time scale of 100 ms.

2.5.1.3 In-Band and Spillover Emissions

The laser shall transmit 95 percent of its energy within ± 20 GHz of its center frequency.

2.5.1.4 Timing Jitter

The Root Mean Square (RMS) pulse timing jitter shall be less than 10 percent of the slot width.

2.5.2 Transmit and Receive Wavelength Selection

The transmit and receive wavelengths shall be switchable through software.

2.5.3 Polarization

Transmitter and receiver pairs should limit polarization mismatch loss to 3 dB. This polarization mismatch loss shall be referenced to an ideal LHCP transmitter and ideal LHCP receiver.

The polarization requirements for T0 are separated into Transmitter and Receiver requirements.

Transmitter Requirements

- Transmitters should transmit signals compatible with LHCP receivers
- Transmitters should transmit LHCP signals

Receiver Requirements

- Receivers should be compatible with LHCP signals

The communications and PAT channel links shall meet the power and link budget requirements as defined in Section 2.5.4 after the permitted losses.

2.5.4 Power and Link Margin

OISL links shall achieve the BER specified in Section 2.6.3.6 with a received irradiance summarized in Table 2-6, below, for each supported baud rate.

Table 2-6: Minimum Irradiance

Baud Rate (Mbaud)	Minimum Irradiance $\mu W / m^2$	Default Maximum Irradiance $\mu W / m^2$
312.5	30	300
625	42	420
1250	60	600

Baud Rate (Mbaud)	Minimum Irradiance $\mu W/m^2$	Default Maximum Irradiance $\mu W/m^2$
2500	85	850
5000	120	1200
10000	170	1700

OISL transmitters shall be capable of delivering a minimum irradiance at the receiver's aperture of 30 $\mu W/m^2$. Note that while specific OISL combinations may result in a reduction in the irradiance at the receiver's aperture required to close the link, each transmitter shall be capable of delivering the specified minimum to ensure the ability to close the link with all receivers.

The maximum irradiance provided by the transmitter shall not exceed the remote receiver's safety threshold. The default maximum safety threshold irradiance is defined in Table 2-6. Each receiver shall be designed to not be damaged by the irradiance values listed.

OISL links shall provide the BER specified in Section 2.6.3.6 with link margin and range as defined by Table 2-7.

Table 2-7: Required Margin at Range

Link Description	Range	Required Margin
Space-to-space	> 5000km and < = 6500 km	1 dB
Space-to-space	Up to 5000 km	3 dB
Space-to-ground	Up to 2800 km	3 dB

2.6 Modulation

2.6.1 Modulation

The data modulation shall be On-Off-Keying Non-Return-to-Zero (OOK-NRZ).

OISLs shall implement a communications channel with a baud rate of 312.5 MHz which shall be frequency locked to the local bus 10 MHz reference clock. Additional baud rates of 625 MHz and 1,250 MHz should be supported. Further communications channels with baud rates of 2,500MHz, 5,000MHz, and 10,000MHz may be supported.

Prior to application of the AM tracking tone, the data modulation shall have an Extinction Ratio greater than 9 dB.

2.6.2 Tracking Tone

Each TX data sequence shall be further modulated with an AM Tracking Tone. The AM Tracking Tone's modulation frequency shall be 40 kHz when the OISL is configured for transmitting wavelength A and shall be 50 kHz when the OISL is configured for transmitting wavelength B.

The nominal AM Tracking Tone Modulation Index (MI) should be 10%, where the MI is defined as:

$$\mathrm{MI} = \frac{(\mathrm{Pmax} - \mathrm{Pmin})}{(\mathrm{Pmax} + \mathrm{Pmin})} \tag{1}$$

as shown in Figure 2-5 below. The AM Tracking Tone:

- Shall be either sinusoidal or a square wave
- Shall have a modulation frequency accuracy of at least 500 PPM
- The AM Tracking Tone shall be remotely controllable
  - The tone shall be controllable (turned on and off) through remote ground command
  - The tone's definition shall be controllable through remote ground command including:
    - Pmax
    - Modulation Index
    - Tone Frequency

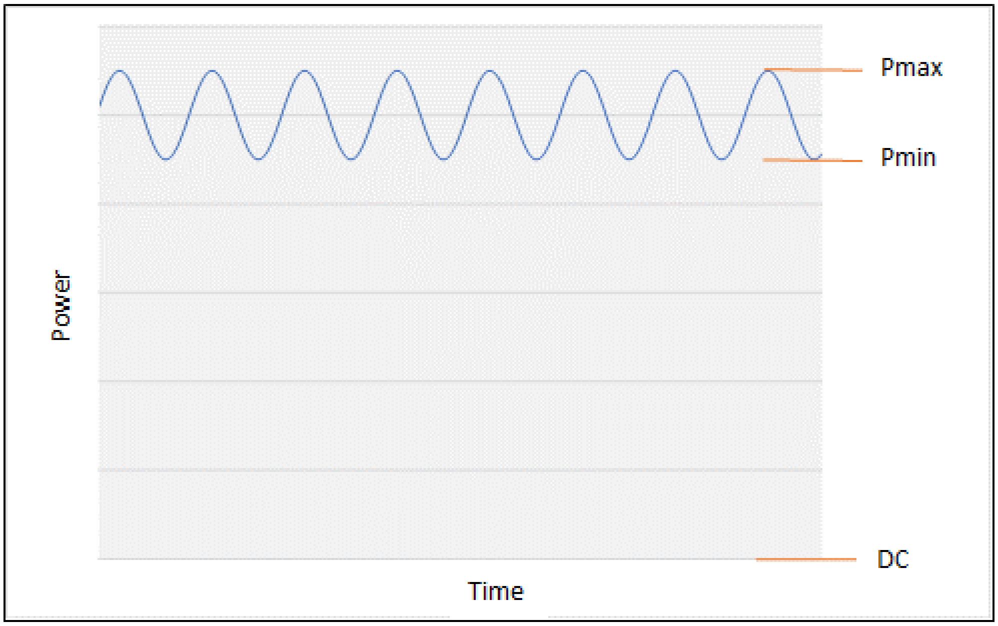

Figure 2-5: AM Tone Tracking Modulation

2.6.3 **Framing, Coding, Encapsulation**

2.6.3.1 Framing Structure

Transmitted frames used by the OISL modem shall adhere to the structure shown in Table 2-8. All transmitted frames in the OISL modem shall be constructed identically: a preamble sequence concatenated with a fixed-length header followed by a fixed-length payload carrying information bits.

After framing and coding, the constituent bits shall be serialized and encoded with line product code (LPC), of rate R=16/24, which actively manages the disparity between the transmitted number of logical ones and zeros.

Table 2-8: Modem Frame Summary

Field	Number of bits	Number of LPC Code Words	Total Number of bits	Comments
Preamble	72	N/A	72	Preamble: 7 2 ’ 77AD5B584364 1E2E26. The MSB (72nd) bit is transmitted first followed in order down to the LSB (1st)
Header	256	256/16 = 16	384	See Section 2.6.3.3
Payload	16320	16320/16 = 1020	24480	See Section 2.6.3.4

Transmission of modem frames shall be synchronous with no pauses between frames and no pauses between any of the bits comprising the frame components in Table 2-8. From the values in Table 2-8, the total frame size shall be 72+384+24480=24936 bits.

2.6.3.2 Preamble Sequence

Every frame shall begin with a Preamble Sequence (PS), which is used by the receiving modem for frame synchronization. The preamble sequence shall be identical for all OISL modem frames and shall take the value shown in Table 2-8.

2.6.3.3 Header

A modem header shall be present in every modem frame immediately following the preamble sequence. The OISL modem frame header shall have these characteristics:

- Modem headers shall be a fixed size (i.e., number of coded bits) for all configurations
- Modem headers shall be protected by a Forward Error Correction (FEC) scheme with a fixed code rate (Section 2.6.3.6.2)
- The payload of the modem header shall be protected by a CRC-16 (Section 2.6.3.6.1.).
- The modem header shall implement the signaling required for the modem features described in the sections below (Table 2-9).

2.6.3.3.1 Header Fields

The frame Header fields are listed in Table 2-9. Exactly one Header shall be present in every modem frame.

Table 2-9: Frame Header Fields

Function	Field	Bits	Description
ARQ	TXFN	16	Sequence number of this (outgoing) TX frame
	RXFN	16	Sequence number of ACK
	ACK	1	ACK (1) or NAK (0) for RXFN
	ACK-valid	1	ACK field is only valid if ACK-valid=1
MAC	FRAME_TYPE	2	00: IDLE
			01: DATA
			10: MGMT
			11: reserved
pseudo-range	TX_TS	40	TX time-stamp (frame egress)
	TOD_SECONDS	6	number of seconds in time-of-day epoch : 0-59
	TS-applies	3	TX_ TS applies to current frame (0), preceding frames (1-7)
Fast Control Channel	FCCH_OPCODE	4	time-multiplexed control signaling
	FCCH_PL	16	Payload contents depends on FCCH_TYPE
reserved		7	header size divisible by 16
CRC	CRC-16	16	See Section 2.6.3.6.1.
Total		128	

The mapping of the fields in Table 2-9 to physical locations in the modem frame is shown in Table 2-10. Here, the column headers indicate the bit number of the byte (MSB: b_7, LSB: b_0) and the row labels indicate the byte number in the header Reed-Solomon codeword. The value 1 shall be assigned to all bits indicated as reserved. A CRC-16 shall be attached to the end of the header with the bits entering the CRC circuit in natural order (byte d_0 to byte d_{13}, MSB first on each byte) and attached to the header in natural order (bytes d_{14} and d_{15}) as illustrated in Table 2-10.

Table 2-10: Mapping of Header Fields to Byte and Bit-locations in the Transmitted Header

	b_7	b_6	b_5	b_4	b_3	b_2	b_1	b_0
d_0	TXFN[7]	TXFN[6]	TXFN[5]	TXFN[4]	TXFN[3]	TXFN[2]	TXFN[1]	TXFN[0]
d_1	TXFN[15]	TXFN[14]	TXFN[13]	TXFN[12]	TXFN[11]	TXFN[10]	TXFN[9]	TXFN[8]
d_2	RXFN[7]	RXFN[6]	RXFN[5]	RXFN[4]	RXFN[3]	RXFN[2]	RXFN[1]	RXFN[0]
d_3	RXFN[15]	RXFN[14]	RXFN[13]	RXFN[12]	RXFN[11]	RXFN[10]	RXFN[9]	RXFN[8]
d_4	1	1	1	1	ACK	ACK-valid	FRAME_TYPE[1]	FRAME_TYPE[0]
d_5	TX_TS[7]	TX_TS[6]	TX_TS[5]	TX_TS[4]	TX_TS[3]	TX_TS[2]	TX_TS[1]	TX_TS[0]
d_6	TX_TS[15]	TX_TS[14]	TX_TS[13]	TX_TS[12]	TX_TS[11]	TX_TS[10]	TX_TS[9]	TX_TS[8]
d_7	TX_TS[23]	TX_TS[22]	TX_TS[21]	TX_TS[20]	TX_TS[19]	TX_TS[18]	TX_TS[17]	TX_TS[16]
d_8	TX_TS[31]	TX_TS[30]	TX_TS[29]	TX_TS[28]	TX_TS[27]	TX_TS[26]	TX_TS[25]	TX_TS[24]
d_9	TX_TS[39]	TX_TS[38]	TX_TS[37]	TX_TS[36]	TX_TS[35]	TX_TS[34]	TX_TS[33]	TX_TS[32]
d_{10}	1	1	TOD_SECONDS[5]	TOD_SECONDS[4]	TOD_SECONDS[3]	TOD_SECONDS[2]	TOD_SECONDS[1]	TOD_SECONDS[0]
d_{11}	1	TS-applies[2]	TS-applies[1]	TS-applies[0]	FCCH_OPCODE[3]	FCCH_OPCODE[2]	FCCH_OPCODE[1]	FCCH_OPCODE[0]
d_{12}	FCCH_PL[7]	FCCH_PL[6]	FCCH_PL[5]	FCCH_PL[4]	FCCH_PL[3]	FCCH_PL[2]	FCCH_PL[1]	FCCH_PL[0]
d_{13}	FCCH_PL[15]	FCCH_PL[14]	FCCH_PL[13]	FCCH_PL[12]	FCCH_PL[11]	FCCH_PL[10]	FCCH_PL[9]	FCCH_PL[8]
d_{14}	CRC-16[15]	CRC-16[14]	CRC-16[13]	CRC-16[12]	CRC-16[11]	CRC-16[10]	CRC-16[9]	CRC-16[8]
d_{15}	CRC-16[7]	CRC-16[6]	CRC-16[5]	CRC-16[4]	CRC-16[3]	CRC-16[2]	CRC-16[1]	CRC-16[0]

2.6.3.3.2 Frame Sequence Numbers

The TX frame sequence number (TXFN, Table 2-9) shall be incremented on every transmitted frame in link session without regard to the FRAME_TYPE. The RX frame sequence number (RXFN) is valid only if pared with an ACK. If ACK valid is zero, then RXFN shall be set to zero.

2.6.3.3.3 Automatic Repeat Request (ARQ)

Header fields supporting implementation of the Automatic Repeat Request modem feature are grouped as the “ARQ” fields in Table 2-9. The ARQ configuration parameters shall remain static for the duration of a session. The ARQ configuration shall only be changed prior to the onset of acquisition. ARQ operation shall be commanded from the ground. ARQ is expected to be used for Space-to-Ground links and may be used for other links.

Only DATA and MGMT frames are be subject to ARQ. IDLE frames shall not be subject to ARQ. The receive terminal is only required to ACK frames received correctly. Successful reception of a frame is defined as the payload CRC-32 passing. Terminals shall treat frames for which an ACK is not explicitly received as NAK’d.

The automatic repeat request scheme shall be configured with the set of parameters in Table 2-11. When operating with ARQ “on,” the receive terminal shall support these configurable ARQ parameters.

Table 2-11: ARQ Parameters

Parameter	Valid Range	Number of bits	Description
ARQ_HOLDOFF_NFRAMES	0,16,32,...4080 N=16 *(0...2^8-1)	8	Window size of ARQ shall be from 0 to (2^8)-1. The maximum value is 16 times 2^8-1=4080. The value of ARQ_HOLDOFF_NFRAMES determines the hold off time: e.g. $256 \times 80\ \mu s$ = 20 ms ARQ HOLDOFF TIME for 312.5 Mbps. Window size and hold-off time are not set independently.
ARQ_MAX_RETX	0-5	3	Maximum number of retransmission attempts.

For ARQ_HOLDOFF_NFRAMES, the range of values is the range required by the interface and does not represent the range of values required to be implemented.

ARQ shall be disabled by setting the number of re-transmission attempts to zero.

The ACK field in the Frame Header (Table 2-9) shall be ignored unless ACK-valid is set to one. When ACK-valid is one, the ACK shall apply to the frame with sequence number RXFN.

The implementation shall buffer received frames such that, after the maximum number of retransmission attempts has been exhausted or all frames have been ACK'd, correctly received FSO frames shall be released to the Ethernet reassembly block (Section 2.6.3.7.7) in order. FSO frames for which an ACK was never received shall be dropped. This scheme produces in-order delivery of Ethernet packets to the space vehicle for all values of ARQ (including settings where ARQ is disabled).

2.6.3.3.4 Timestamps

The TX PHY shall apply a timestamp in the header of every modem frame (TX_TS field, TOD_SECONDS, Table 2-9). The implementation shall reference the applied timestamp to the egress point of the rising edge of the first bit of the modem frame (exiting the aperture). The TS-applies header bit indicates if the TS applies to current frame (0) or preceding frames (1-7).

2.6.3.3.5 Fast Control Channel (FCCH)

The OISL modem frame shall provide an embedded fast control channel (FCCH). The FCCH is a low- rate channel with reserved bandwidth for robust, low-latency transport of short messages between OISL terminals. The FCCH enjoys the benefit of both error detection (via the Header CRC) and error correction (via the Header FEC) by virtue of residing in the frame Header. No ARQ is provided for the FCCH channel.

The FCCH physical channel shall be time-multiplexed:

- FCCH_OPCODE (4 bits): opcode which determines the format of the FCCH payload
- FCCH_PL (16 bits): payload bits

A single FCCH shall be transmitted and received in every frame and can be valid for every FRAME_TYPE (Table 2-9 and Section 2.6.3.5).

The higher layers of the modem divide the capacity of the FCCH physical channel into multiple logical channels through time-multiplexing. The effective average data rate of these logical channels is a function of the payload FEC, baud rate, and the frequency of which the logical channel is scheduled by the modem higher layers. The FCCH logical channels are defined in Table 2-12. If no data is waiting for transport, the FCCH opcode 1111 shall be specified. In this case the FCCH payload bits shall be all logical ones. Payload values for Reserved opcodes shall be all logical zeros.

Table 2-12: FCCH Logical Channels

Description	FCCH _TYPE	Opcode (4 bits)	Message Rate
Link Quality Reports	LAPC_CRC_ERROR_REPORT	0000	1 Hz
	LAPC_RSSI_FAST	0001	100 Hz
	LAPC_RSSI_SLOW	0010	1 Hz
	LAPC_SYNC_REPORT	0011	1 Hz
	LAPC_FEC_CORRECTED_ERROR_REPORT	0110	1 Hz
OISL Reports	OISL_SENSITIVITY	0100	1 Hz
	OISL_CAPABILITIES	0101	1 Hz
Reserved	RESERVED	0111-1110	
Not Present	N/A	1111	

The payload for each FCCH message shall be 16 bits. Payloads for each of the FCCH_TYPES are defined in Table 2-13.

Table 2-13: FCCH Payloads

FCCH_TYPE	Field	Bits	Bit Positions	Description
LAPC_CRC_ERROR_REPORT (Opcode = 0000)	LAPC_RPT_CRC_ERROR	16	15-0	Number of frame CRC errors in the last second. Note: Where a CRC error bit is defined as an error in either the header or payload CRC
LAPC_RSSI_FAST (Opcode = 0001)	LAPC_RPT_RSSI_FAST	14	15-2	Received Signal Power at aperture LSB = 75 nW/m² The reported value shall only cover the last 10 ms and shall not be integrated over a longer time period.
	LAPC_RPT_FS_FAST	2	1-0	Frame sync status, last 10 msec.
				00: not locked (experienced one or more sync losses during the period)
				01: locked (for full period)
				10: reserved
				11: reserved
LAPC_RSSI_SLOW (Opcode = 0010)	LAPC_RPT_RSSI_MEAN	8	15-8	Received power at aperture mean (average, trailing 1 sec from 1 PPS, step size = -0.25086 dBm/m^2)
	LAPC_RPT_RSSI_SDEV	8	7-0	Received Power at aperture standard deviation (average, trailing 1 sec from 1 PPS, step size = -0.25086 dBm/m^2)

Table 2-13: FCCH Payloads

LAPC_SYNC_REPORT (Opcode = 0011)	LAPC_RPT_FS_LOSS	14	15-2	Number of times frame sync lost (trailing 1 sec from 1 PPS)
	LAPC_RPT_FS_STATE	2	1-0	Frame sync status (at 1 sec sample time)
				00: not locked (experienced one or more sync losses during the period)
				01: locked (for full period)
				10-11: reserved; reserved values shall be set to all zeros.
OISL_SENSITIVITY (Opcode = 0100)	OISL_PMIN	8	15-8	Required optical power at aperture (step size = -0.25086 dBm/m^2)
	OISL_PMAX	8	7-0	Maximum RX optical power at aperture permitted (step size = -0.25086 dBm/m^2)
OISL_CAPABILITIES (Opcode 0101)	MAJOR_VERSION	5	15-11	The SDA Standard Version is specified as three integers separated by periods in the format MAJOR_VERSION.MINOR_VERSION.PATCH_VERSION. For example: SDA Standard revision (here 2.1.2): Major=00010; Minor=00001; Patch=00010
	MINOR_VERSION	5	10-6	
	PATCH_VERSION	6	5-0	

Table 2-13: FCCH Payloads				
LAPC_FEC_CORRECTED_ERROR_REPORT (Opcode = 0110)	LAPC_RPT_FEC_ERRORS_CORRECTED	16	15-0	Number of frames that require FEC correction per second. Note: Frames where an FEC correction is performed in either the header or payload

To ensure standardization of implementation for LAPC_RSSI_SLOW, the equations are shown below. The statistical measurement shall be performed on linear power readings I_n.

$$\text{LAPC\_RPT\_RSSI\_MEAN} = \frac{1}{N} \cdot \sum_{N} I_n$$

$$\text{LAPC\_RPT\_RSSI\_SDEV} = \sqrt{\frac{1}{N} \cdot \sum_{N} (I_n - LAPC\_RTP\_RSSI\_MEAN)^{2}}$$

The LAPC_RSSI_SLOW power figures inside the FCCH shall represent the received power at aperture expressed in logarithmic scale with a LSB of -0.25086 dBm/m^2. This is expressed by the following formula using the LSB x:

$$LAPC\_RPT\_RSSI\_MEAN = (x * -0.25086)\,\frac{dBm}{m^2}$$

$$LAPC\_RPT\_RSSI\_SDEV = (x * -0.25086)\,\frac{dBm}{m^2}$$

Example: The mean value of 1mW (0 dBm) and 0.01mW (-20 dBm) is 0.505 mW = -2.97 dBm
and not (0 dBm + -20dBm)/2 = -10 dBm

The frequency at which the FCCH messages are sent is application dependent subject to these requirements:

- LAPC_RSSI_FAST_REPORT shall be sent at rate at least 100 Hz.
- LAPC_CRC_ERROR_REPORT, LAPC_RSSS _REPORT, and LAPC_SYNC_REPORT
- LAPC_FEC_ERROR REPORT is a recommended, but optional report. If utilized, it will be sent at rate of at least 1 Hz

OISL_SENSITIVITY shall be sent at 1 Hz and is used by the receiving terminal to control transmit optical power based on LAPC_RSSI_REPORT messages.

The OISL_CAPABILITIES is for future use for autonomous OISL Link configuration.

The OISL implementation shall be designed to tolerate loss of any FCCH messages.

2.6.3.4 Payload

2.6.3.4.1 Data Bytes

All modem frames shall carry a payload of 239×8-4=1908 application data bytes with 8 bits per byte. The source of data bytes for DATA frames (FRAME_TYPE=01, Table 2-9) shall be encapsulated Ethernet traffic.

2.6.3.4.2 CRC-32

All modem frames shall protect the integrity of the payload information bits with an attached 32-bit CRC (Section 2.6.3.6.1).

2.6.3.4.3 Parity Bytes

The OISL modem features payload FEC. The payload FEC shall be implemented as detailed in Section 2.6.3.6.3 and shall adhere to [2] Section 4.1.4. The number of parity bytes is (255-239) × 8=128.

2.6.3.5 Special Frames

The field frame Header shall contain a FRAME_TYPE field. The FRAME_TYPE field of the frame Header (Table 2-9) shall signal the type of modem frame. This section defines the frame types and their intended usage on the optical interface. Features signaled through the frame header are available in all frame types.

2.6.3.5.1 IDLE Frames

By design the modem always transmits frames with no gap between adjacent frames. In the case that data is not available for transmission the modem shall insert consecutive IDLE frames into the transmitted stream until other types of traffic frames become available. There shall not be a gap between frames under any circumstance.

2.6.3.5.1.1 Header Construction

Modem IDLE frames shall be signaled in the frame header by field FRAME_TYPE=00 (Table 2-9). Modem IDLE frame headers shall be otherwise identical to normal data frame headers with the exception that the TXFN field in an IDLE frame header is always equal to the master TXFN counter.

2.6.3.5.1.2 Payload Construction

Modem IDLE frames shall be subject to the same payload FEC and shall be protected by the same CRC-32 as the data frames.

The information payload in IDLE frames shall be constructed as a pseudo-random binary sequence (PRBS) using the same generator as the frame scrambler (Section 2.6.3.6.4) except with its initial seed equal to the value of the frame header TXFN field (Table 2-9) plus one.

The size of the IDLE information payload shall be the same as for data frames.

The bits from the pseudo-random binary sequence shall be written into the modem frame in the (common) order described in Section 2.6.3.5.3.2 and illustrated in Figure 2-7.

2.6.3.5.2 MGMT/PNT Frames

The MGMT frame type is provided for management frames. These frames shall be used for inter-OISL communications.

MGMT frames **shall** be sent at 1Hz, each holding 1 time-stamp measurement set.

2.6.3.5.2.1 Header Construction

Modem MGMT frames shall be signaled in the frame header by field FRAME_TYPE=10 (Table 2-9).

2.6.3.5.2.2 Payload Construction

Modem MGMT frames shall be subject to the same payload FEC and are protected by the same CRC-32 as the data frames. The size of the MGMT information payload shall be the same as for data frames.

The bytes comprising the MGMT frame payload shall be written into the modem frame in the (common) order described in Section 2.6.3.5.3.2 and illustrated in Figure 2-7.

2.6.3.5.2.3 Payload Frame Definition

The MGMT/PNT Frames are used to communicate OISL frame timestamps and calculated range and range timestamp between the OISLs. Table 2-14 defines the MGMT/PNT payload.

Table 2-14: MGMT/PNT Frame Payload Definition for Ranging Timestamps.

Field	Bits	Bit Positions	Description
RX_PHY_Timestamp_sec	6	0-5	RX PHY timestamp for frame receipt Seconds of the whole GPS minute (0 Hour, January 6, 1980)
RX_PHY_Timestamp_picosec	40	6-45	RX PHY timestamp for frame receipt Picoseconds of the whole second
TX_PHY_Timestamp_sec	6	46-51	TX PHY timestamp for the same frame associated with the RX PHY Timestamp Seconds of the whole GPS minute (0 Hour, January 6, 1980)

Field	Bits	Bit Positions	Description
TX_PHY_Timestamp_picosec	40	52-91	TX PHY timestamp for the same frame associated with the RX PHY Timestamp Picoseconds of the whole second
Range_Meters	64	92-155	Computed and provided TX OISL aperture to RX OISL aperture range in meters, IEEE 754 double precision floating point format. This field must be populated. Calculation of this field is optional - If not calculated, this field shall be set to 0 (zero).
Range_TimeStamp_sec	32	156-187	Computed range timestamp: whole seconds of GPS time from epoch 0hour, Jan 6, 1980. Calculation of this field is optional - If not calculated, this field shall be set to 0 (zero).
Range_TimeStamp_picosec	40	188-227	Computed range timestamp: picoseconds of the whole second of GPS time Calculation of this field is optional - If not calculated, this field shall be set to 0 (zero).
Timestamp_Valid	1	228	1 = range estimate is valid; 0 = range estimate is not valid.

Note: The average value of the first and last timestamp used for the range calculation shall be associated to the range measurement and reflected as Range_TimeStamp.

2.6.3.5.3 DATA/IDLE/MGMT Frame Handling

2.6.3.5.3.1 Multiplexing

The modem shall multiplex the modem frame types (FRAME_TYPE, Table 2-9) for transmission as illustrated in Figure 2-6.

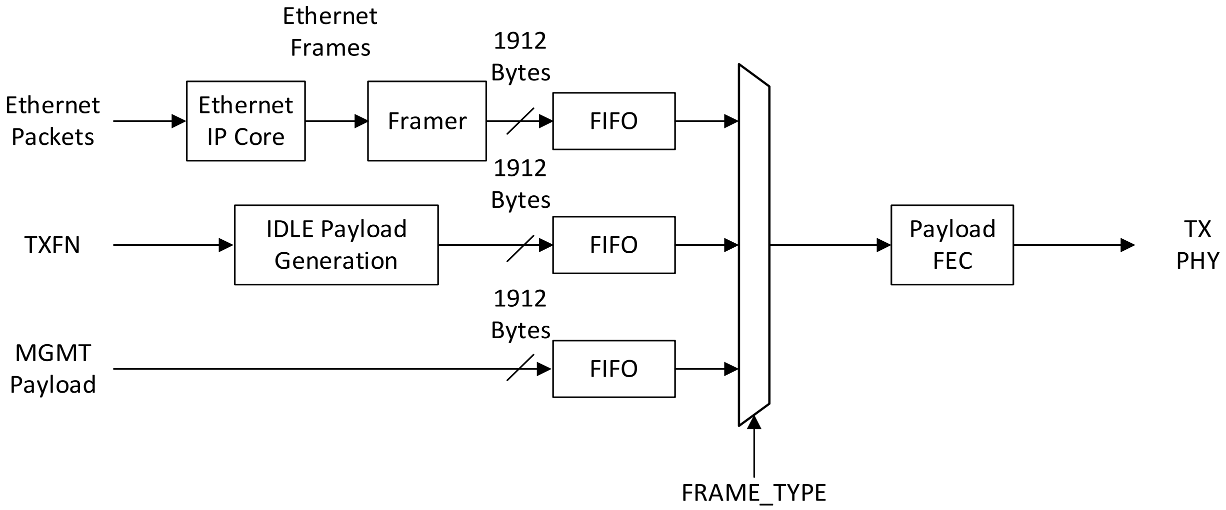

Figure 2-6: Multiplexing Frame Types

Ethernet traffic shall be encapsulated (Section 2.6.3.7) and carried solely in DATA frames (FRAME_TYPE=01, per Table 2-9). If neither a DATA frame nor a MGMT frame (FRAME_TYPE=10) is ready for transmission, the modem shall continuously transmit IDLE frames (FRAME_TYPE=00). Arbitration between DATA and MGMT frames for transmission shall be implementation dependent. The offered traffic load of MGMT frames should be sparse, on the order of 0 -10 Hz, depending on the application's PNT configuration (Section 2.6.3.7.8).

2.6.3.5.3.2 Byte Ordering and CRC-32 computation

Payload data shall be written into the modem frame in the logical order shown in Figure 2-7 for all values of FRAME_TYPE (Table 2-9). The mapping from logical order (Figure 2-7) to physical order (Figure 2-10) shall be identical for all payload types and is described in Section 2.6.3.6.3.

The payload CRC-32 shall be computed with bytes entering the CRC-32 circuit in this order (Figure 2-7): word 0: bits[7:0], bits[15:8], bits [23:16], then bits[24:31], followed by the same ordering for word 1, counting naturally through the bytes comprising the payload up through the end of word 476. The bits of each byte shall enter the CRC computer in a manner that's equivalent to the bit-serial reference implementation of the CRC-32 (Figure 2-8) with bytes entering MSB first and LSB last.

The computed checksum shall be written into the frame (logical order, Figure 2-7) with the 32 bits exiting the CRC reference circuit written naturally into word 477 starting at bit 31 down to bit 0.

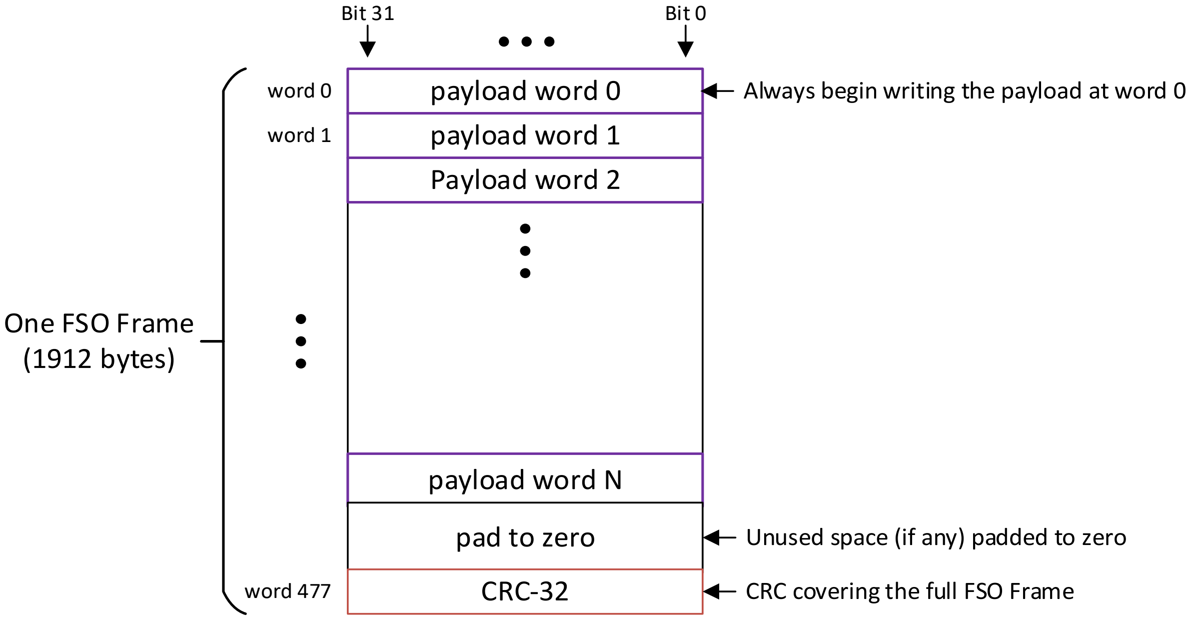

Figure 2-7: Payload Byte Ordering

After staging, the 1912 bytes shall be subject to payload FEC encoding and interleaving (Section 2.6.3.6.3). Note that for IDLE frames the number of zero-pad bytes shall be zero. The number of zero-value pad bytes for MGMT will depend on the application's definition of the MGMT frame payload format. The MGMT frame payload shall never exceed 1908 bytes.

2.6.3.6 Error Control Coding

The bit error rate (BER) requirements are as follows:

- OISLs shall achieve a decoded BER after FEC of 10^{-6}
- OISLs should achieve a decoded BER after FEC of 10^{-9}

These error rates are to be achieved through OISL modem frames with forward error control coding:

- Information bits shall be protected by CRC's (Section 2.6.3.6.1., header: 16 bits, payload: 32 bits)
- Fixed-rate (shortened) Reed-Solomon code shall be used for the frame Header (Section 2.6.3.6.2)
- Fixed-rate Reed-Solomon code shall be used for the frame Payload (Section 2.6.3.6.3)

2.6.3.6.1 CRC

Two CRC's are required to generate the modem frame: a CRC-16 protects the frame header bits while a CRC-32 protects the payload bits. A functional description of a generic L-bit CRC encoder circuit is shown in Figure 2-8. The circuit consists of an L-bit register ($L = 16$ for CRC-16 and $L = 32$ for CRC-32). The connection polynomials (i.e., values g_k) are defined in Table 2-15 for each of the two CRC's required to create the modem frame.

Calculation of the CRC for a block of k payload bits shall be performed as follows:

- Initialize the L-bit encoder register state to zero at the start of each new CRC calculation
- Clock in the k payload bits with switches S_1 and S_2 both in the down position
- After the last payload bit has been loaded the encoder register contains the L-bit CRC value. It can be clocked-out with switches S_1 and S_2 in the up position.

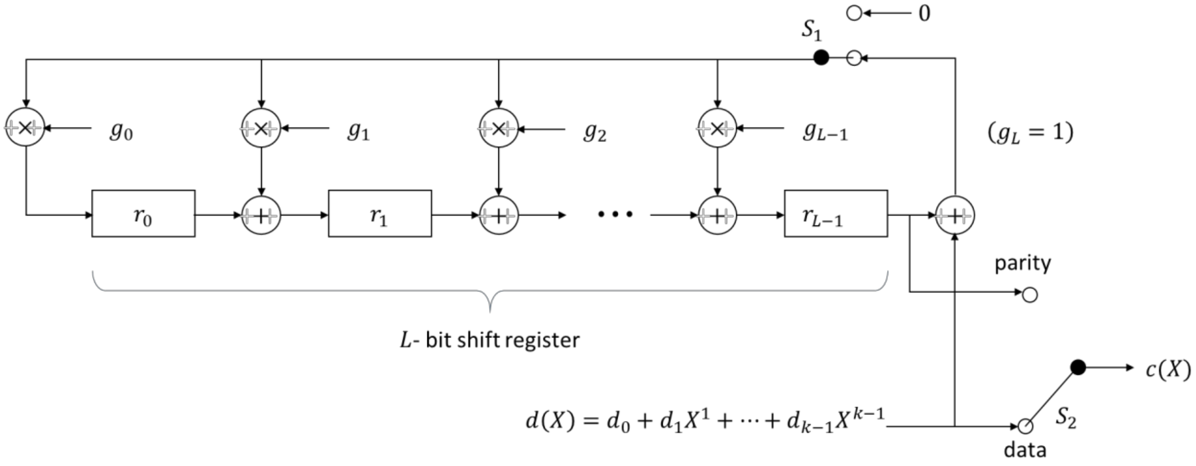

*Figure 2-8: **L**-bit CRC Calculation Circuit*

Table 2-15: CRC Polynomials

Location	Length	Polynomial	Source
Frame Header	16 bits	$g(x) = x^{16} + x^{12} + x^5 + 1$	1
Frame Payload	32 bits	$g(x) = x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$	1

2.6.3.6.2 Header FEC

The modem header payload shall be encoded by a shortened Reed-Solomon code. The shortened Reed-Solomon code shall be constructed by zero-valued virtual fill based on the same RS(255, 239) code as used for the payload FEC described in Section 2.6.3.6.3.

The header RS code parameters are provided in Table 2-16.

Table 2-16: Shortened Reed-Solomon Code for Frame Header

Parameter	Value (bytes)	Comments
N	255	Number of codeword bytes
K	239	Number of data bytes (including vfill bytes)
vfill	223	Number of zero-valued virtual fill bytes

Virtual fill bytes shall be padded at the beginning of the Reed-Solomon codeword but shall not be transmitted. After shortening, the header is effectively encoded by an RS(32,16) code. The encoding process for the frame header is presented in Figure 2-9.

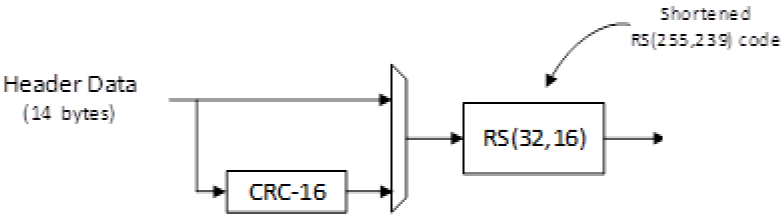

Figure 2-9: Header FEC Encoding

2.6.3.6.3 Payload FEC and Interleaving

The OISL payload FEC shall be adapted from the Reed-Solomon code specified in [4].

The Reed-Solomon (RS) encoding of the payload FEC shall follow the recommendations in [4] with these specifications:

- In the event that the payload has fewer than 1908 bytes to transmit, the higher layer shall pad the data block with zeros to fill the entire 1908 bytes
- A CRC-32 check value shall be appended to the block of 1908 source bytes prior to encoding
- The payload RS FEC shall encode blocks of 239×8=1912 bytes of source data across 8 RS(255,239) codewords
- The RS code shall be 8 bits per RS symbol ([4], Section 4.3.1) with an encoded block size (per codeword) of 255 symbols
- The number of parity digits shall be 16, producing an RS(255,239) code, corresponding to $E = 8$ in ([4], Section 4.3.2)
- The Galois Field generator polynomial shall be $F(x) = x^8 + x^7 + x^2 + x + 1$
- The RS code generator polynomial shall be $g(x) = \prod_{j=128-E}^{127+E}(x - \alpha^{11j})$
- The RS codewords shall be in systematic form with data symbols preceding parity symbols
- The RS codewords shall be defined on the conventional (powers of α) basis. This is a departure from ([4], Section 4.3.9) which specifies the Berlekamp Dual basis

The interleaving depth for the payload FEC shall be 8 RS(255,239) codewords, as illustrated notionally in Figure 2-10. This diagram, abstracted from ([4], Section 4.2), illustrates notionally how source bytes are encoded.

- Source bytes are written in column-major order, spreading contiguous input bytes across all 8 Reed-Solomon codewords
- Source bytes are written in systematic form with the block of data bytes followed by a block of parity bytes
- After encoding, bytes are transmitted in the same order as they entered the encoder (column major, per Figure 2-10) with the block of data bytes followed sequentially by the block of parity bytes

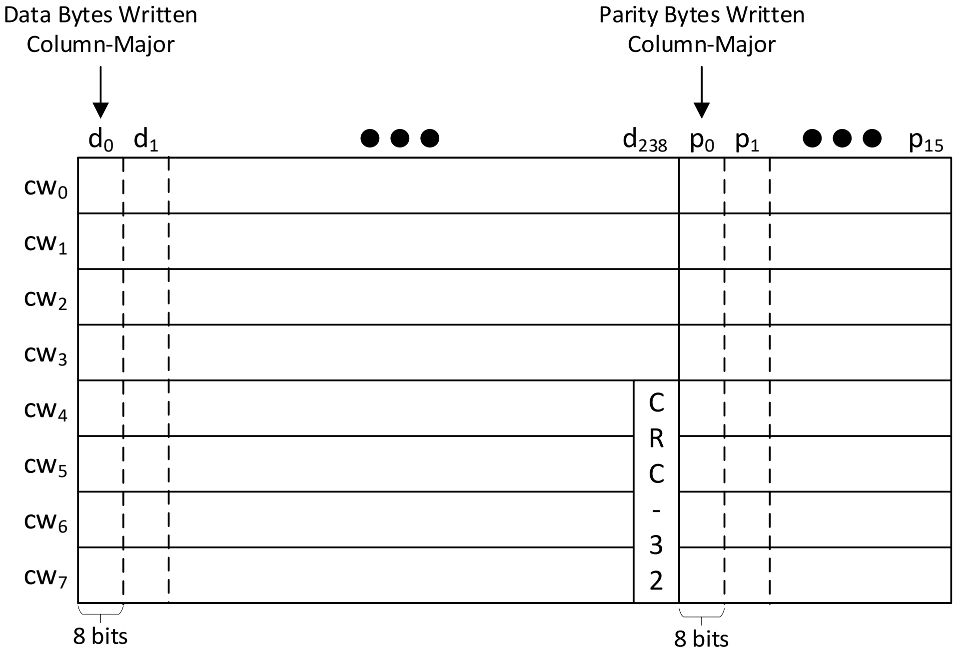

Figure 2-10: Payload FEC Interleaving

The transmit order of each 8-bit Reed-Solomon encoded interleaved symbol (an 8-bit byte) is shown in Figure 2-11.

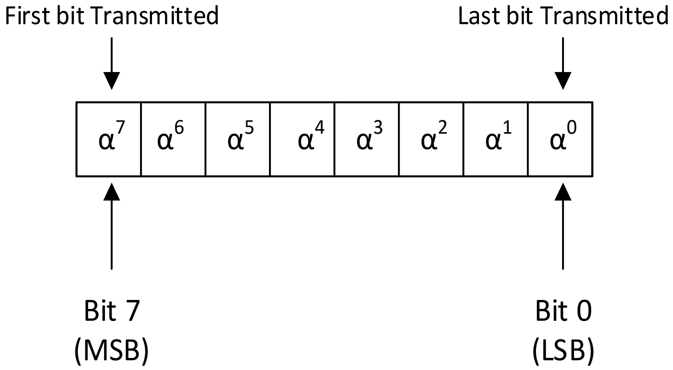

Figure 2-11: Bit Ordering of Reed-Solomon Encoded Bytes

These following adaptations are made from the payload FEC framing as specified by [2]:

- The SDA OISL shall only implement the "LIA Framing" section of the [2], meaning that all incoming payloads to the FEC are fixed sized. Therefore, the 8 bytes allocated by [2], for the LIAU superframe headers are subsumed into the payload section of the FEC encoder. This increased the "data" section in Figure 2-10 from 238 to 239 bytes and conforms to a standard Reed-Solomon codeword as defined in ([2] Section 4).
- All OISL modem frames carry a 15264 information bit payload per frame which is protected by a CRC-32. The inclusion of the CRC-32 in Figure 2-10 is an extension of the CCSDS framing specification.

The SysChanDat* bit of the LPC(25,16) code (as described in CCSDS 141.11-O-1, Section 3.3.2.3.4) is not used in this standard. Here, we use the same LPC code as the referenced CCSDS standard except without the SysChanDat* bit, producing an LPC(24,16) code. The LPC code is applied synchronously during frame generation (see Figure 2-15) beginning with the first bit of the header and continuing through the last bit of the payload. The LPC code is not applied to the preamble.

- The OISLs may be synchronized by simple cross-correlation with the frame preamble.

2.6.3.6.4 Scrambling and Line Product Code

The scrambler and Line Product Code (LPC) shall be implemented and shall be adopted from [2]. The scrambler follows ([2] Section 3.3.2.3.3.1) with details of its initial seed provided in Section 2.6.3.6.5 of this Standard.

- The scrambler shall reset to a fixed value (Table 2-17) at the start of every modem header.
- The scrambler shall advance naturally after scrambling the header to also scramble the payload bits.
- The preamble bits shall not be scrambled.

2.6.3.6.5 Scrambler Reset State

The scrambler shall initialize the PRBS generator stages with the value defined in Table 2-17. The 25-bit value for the scrambler initial state in the table shall be read (hex) as 0x0000007.

Table 2-17: Scrambler Reset Definition

X[24:0]	Remarks
X[0:1]=1 X[2]=1 X[24:3]=0	Initialization Pattern

2.6.3.6.6 Scrambler Initialization

After a system reset, the PRBS generator shall start with the initialization pattern as defined in Table 2-17. The scrambler shall be reset to the value in Table 2-17 at the start of every modem frame.

2.6.3.6.7 Scrambler Parallel Implementation Overview and Bit Ordering

The scrambler defined in [2] refers to the bit-serial implementation of the scrambler. The implementer may use a bit-serial representation or unroll it in a parallel implementation. Bit- and byte-ordering are defined using the bit-serial reference implementation of the standard to avoid ambiguity.

The scrambler is applied to all data bytes from both the Header and Payload Reed-Solomon encoders prior to LPC encoding. Only the 72-bit preamble sequence is not scrambled. The scrambler shall be applied as illustrated in Figure 2-12. For each pair of bytes entering the scrambler, the bits shall enter the scrambler in the order byte 0 (MSB) to byte 1 (LSB) as illustrated in the figure. Bytes shall enter the scrambler in natural order from the encoded header followed by the encoded payload.

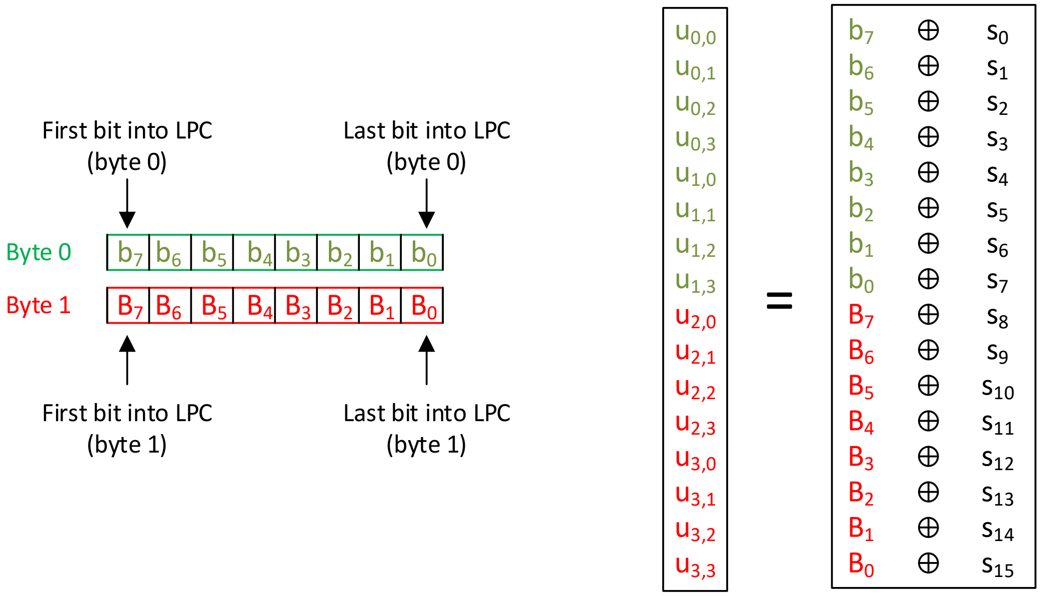

Figure 2-12: Application of the Scrambler

The ingress bits are scrambled as the exclusive or of the bits produced by the scrambler PRBS in natural order. Per Figure 2-12, the scrambler PRBS shall be constructed with the polynomial from ([2] Section 3.3.2.3.3) where, after initialization to the state from Table 2-17 at the start of every header, the bits s_k represent the natural (in-order) outputs from the scrambler PRBS, advancing without reset of its state while the totality of the header and payload bytes are scrambled.

2.6.3.6.8 Line Product Code

The LPC(24,16) code and running disparity manager is adopted from ([2] Section 3.3.2.3.4) with optional SysChanDat* bit punctured.

- The LPC(24,16) code is applied synchronously with frame generation (see Figure 2-15).
- The frame preamble has zero disparity (by design) and is not subject to the LPC code.

- The frame header is synchronous to the frame preamble with the header size exactly a multiple of 24 bits, meaning that the header exactly fits in an integer number of LPC code blocks.
- The frame payload (information bits, CRC, and parity bits) is synchronous to the frame header and is also dimensioned to produce an integer number of LPC codewords.

The ingress bits to the LPC encoder shall be first scrambled (Section 2.6.3.6.6). After scrambling, the bits shall be differentially encoded as illustrated in Figure 2-13 where the notation for the differentially encoded bits has been adapted from ([2] Section 3.3.2.3.4.4).

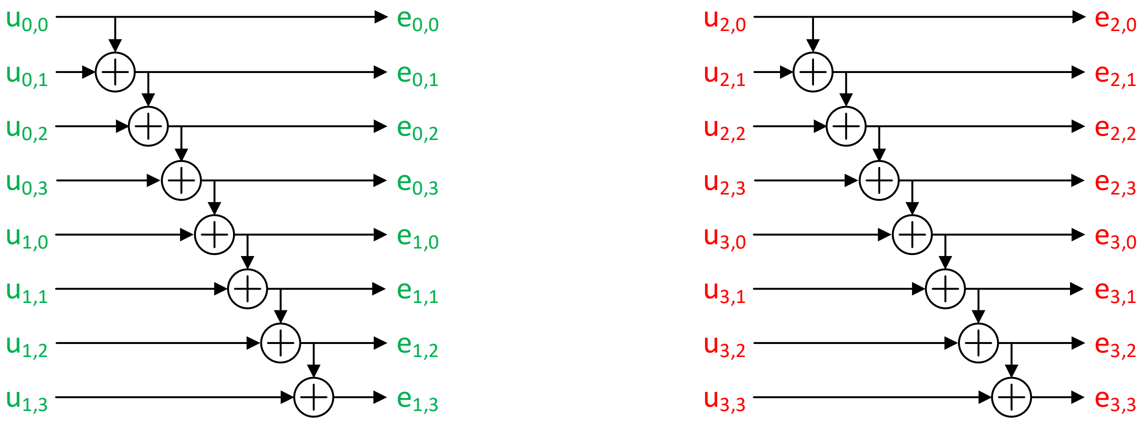

Figure 2-13: Differentially Encoding in LPC Encoder

After differentially encoding, horizontal and parity bits are computed (per [2] Sections 3.3.2.3.4.4.2 and 3.3.2.3.4.4.3, respectively). Active disparity management shall be applied ([2] Section 3.3.2.3.4.5). The LPC-encoded bits are represented as shown in Figure 2-14.

$e_{0,0}$	$e_{0,1}$	$e_{0,2}$	$e_{0,3}$	ph_0
$e_{1,0}$	$e_{1,1}$	$e_{1,2}$	$e_{1,3}$	ph_1
$e_{2,0}$	$e_{2,1}$	$e_{2,2}$	$e_{2,3}$	ph_2
$e_{3,0}$	$e_{3,1}$	$e_{3,2}$	$e_{3,3}$	ph_3
pv_0	pv_1	pv_2	pv_3	

Figure 2-14: LPC Codeword

The transmission order of the LPC-encoded bits, after active disparity management, shall be: $\{e_{0,0}, e_{0,1}, e_{0,2}, e_{0,3}, e_{1,0}, e_{1,1}, e_{1,2}, e_{1,3}, e_{2,0}, e_{2,1}, e_{2,2}, e_{2,3}, e_{3,0}, e_{3,1}, e_{3,2}, e_{3,3},$

$$ph_0, ph_1, ph_2, ph_3, pv_0, pv_1, pv_2, pv_3\}$$

with bit $e_{0,0}$ entering the channel first and bit pv_3 transmitted last of the LPC codeword.

2.6.3.6.9 Frame Generation Summary

Construction of the OISL frame and its integration with the line product code is summarized in Figure 2-15.

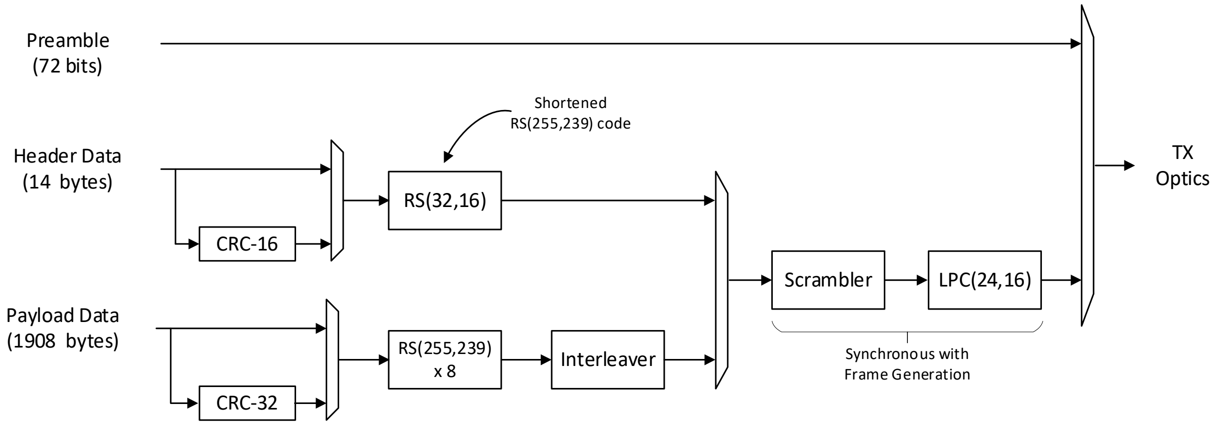

Figure 2-15: Frame Encoding Summary

2.6.3.7 Ethernet Packet Encapsulation

2.6.3.7.1 Overview of Ethernet Packet Encapsulation

The OISL data plane encapsulates Ethernet packets as Free Space Optical (FSO) frames for transport across the optical link. The processing steps are illustrated functionally in Figure 2-16.

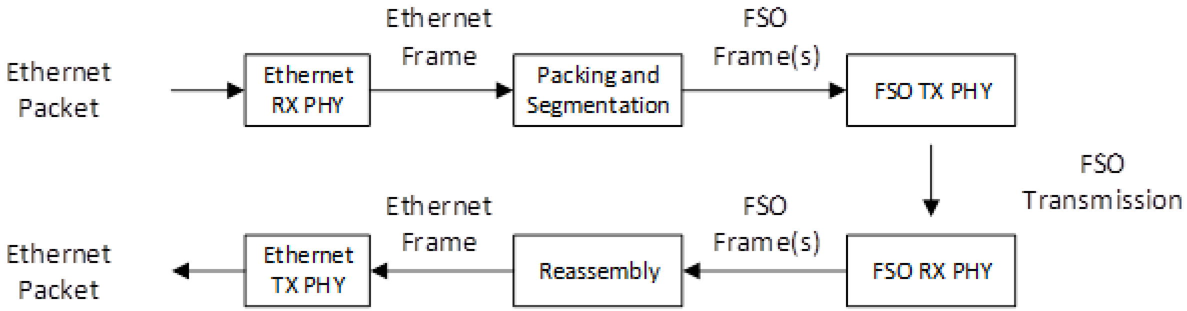

Figure 2-16: Ethernet Encapsulation

This scheme permits the OISL to carry virtually any form of Ethernet traffic transparently between a pair of optical terminals. The presence of the OISL is largely transparent to the endpoints.

2.6.3.7.2 Ethernet Packet Handling

On ingress to the modem, the Ethernet frame shall be extracted from every Ethernet packet by stripping the Preamble and the Start Frame Delimiter (SFD) from the packet. The Ethernet frames shall be queued to the Packing and Segmentation block for encapsulation as FSO frames.

On egress from the modem, the TX Ethernet PHY shall construct Ethernet packets from the received (reconstructed) Ethernet frames by pre-pending for each frame the Ethernet Preamble,Start Frame Delimiter (SFD), and appending an appropriate Interpacket Gap (IPG). The reconstructed Ethernet packet shall be emitted by the Ethernet PHY.

2.6.3.7.3 Packing and Segmentation

The *Packing and Segmentation* operation (Figure 2-16) shall perform the following functions in the TX PHY of the optical terminal:

- Segments large Ethernet frames into one or more FSO frames (as needed)
- Packs small Ethernet frames into FSO frames

The implementation of the *Packing and Segmentation* operation shall preserve the ingress order of Ethernet packets.

2.6.3.7.4 FSO Frame Payload Format

This section defines how the output of the Packing and Segmentation operation is formatted in the payload section of an FSO DATA Frame. The structure is illustrated logically in Figure 2-17. The bytes shall be written into the payload FEC physical frame in the byte order specified in Figure 2-10. The bytes shall be consecutive, per word in Figure 2-17, with the lower 8 bits (0 to 7) denoting the first byte, followed by the next grouping of bytes up to the upper set of 8 bits (24 to 31) denoting the fourth byte. The numbering of bytes for the purpose of defining their ordering entering the payload FEC shall count up naturally for each 32-bit word in Figure 2-17.

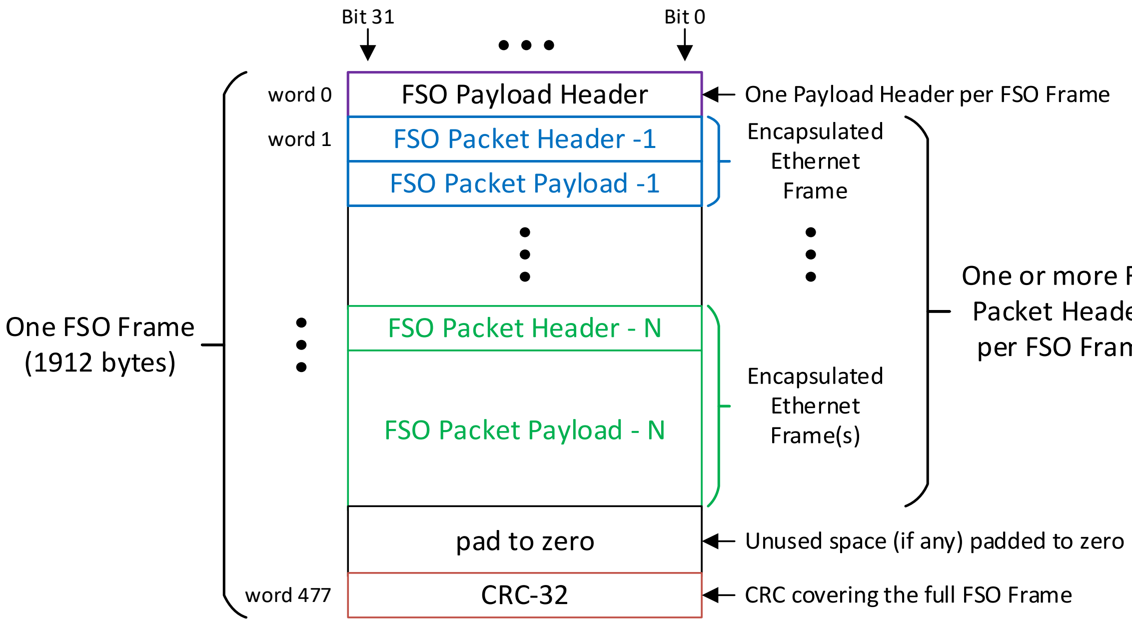

Figure 2-17: FSO Payload Frame Format

The FSO Payload and FSO Frame headers split Ethernet frame payloads across multiple frames, enabling efficient packing of Ethernet frames into FSO frames.

There shall not be any zero-pad space except at the end of the FSO frame as illustrated in Figure 2-17.

Note that the CRC-32 described in Figure 2-17 is the same CRC-32 previously described in Figure 2-10 and is repeated here for clarity.

2.6.3.7.5 FSO Payload and Packet Headers

Every FSO frame shall start with an FSO Payload Header. There shall be exactly one FSO Payload Header (32 bits) per FSO frame. The contents of the FSO frame and packet headers shall follow the definition presented in Table 2-18.

Table 2-18: FSO Payload and Packet Headers

	Field	bit numbers	#bits
FSO Payload Header (32 bits)	0xAB	31:24	8
	seq_num	23:14	10
	Length	13:0	14
FSO Packet Header (32 bits)	0xCDEF	31:16	16
	reserved	15:14	2
	Length	13:0	14

FSO Payload Header:

The FSO Payload Header shall be constructed as an 8-bit magic number (0xAB) followed by a 10-bit sequence number and a 14-bit length field. Sequence numbers shall increment sequentially for every DATA frame and wrap naturally around zero. The sequence number referenced in Table 2-18 is unrelated to the modem's ARQ signaling in Table 2-9.

The system shall be capable of splitting an encapsulated Ethernet frame payload across multiple FSO frames. The FSO Payload Header length field shall have a non-zero value only when an Ethernet frame is segmented across the preceding and current FSO DATA frames, signaling the length of the preceding encapsulated packet remaining. Otherwise, the length field shall be zero.

FSO Packet Header:

The FSO packet header (Table 2-18) shall signal encapsulation of an Ethernet frame. The header shall be constructed as a 16-bit magic number (0xCDEF) followed by two reserved bits (0b00) and a 14-bit length field. The length field shall signal the number of payload bytes to follow where the length field excludes the length of the FSO packet header regardless of whether the Ethernet frame is segmented into the following FSO frame.

2.6.3.7.6 Ethernet Byte Ordering, Padding, and CRC

FSO packet headers shall be aligned to a 32-bit boundary. If the encapsulated Ethernet frame length is not a multiple of 4 bytes, the implementation shall pad the remaining unused space in the FSO frame with zeros.

Ethernet frame payload bytes shall be written into the FSO frame (Figure 2-17) in natural (ascending) order with the first ingress byte of the Ethernet frame written into the first word after the FSO Packet header starting at byte 0 (bit positions [7:0]), incrementing up through byte 3 (bit positions [31-24]), then incrementing to the next word in the FSO frame. Unused bytes in the FSO frame shall be padded with zeros.

An example of the byte ordering for the encapsulation of a hypothetical Ethernet frame of length n bytes is illustrated in Table 2-19. The Payload Header (Table 2-18) is written into FSO frame word 0. In this example, suppose that there is no Ethernet frame continued from a preceding FSO frame. Then a Packet Header is written into FSO frame word 1. This marks the start of the encapsulated Ethernet frame bytes. The bytes of the Ethernet frame (ETH_Byte_0, ..., ETH_Byte_n) are written sequentially in the natural (ascending) byte order in which they were received starting in the first FSO word following the Packet Header until either the entire Ethernet frame is written or the available space in the FSO frame is consumed.

Table 2-19: Ethernet Frame Byte Ordering into FSO Logical Frame

<table>
<tr><td>FSO word number</td><td>contents</td><td>31-24</td><td>23-16</td><td>15-8</td><td>7-0</td></tr>
<tr><td>word 0</td><td>Payload Header</td><td colspan="4">AB[31:24], seq_num[23:14], length[13:0]</td></tr>
<tr><td>word 1</td><td>Packet Header</td><td colspan="4">CDEF[31:18], reserved [17:16], length[13:0]</td></tr>
<tr><td>word 2</td><td>Ethernet bytes</td><td>ETH_Byte_3</td><td>ETH_Byte_2</td><td>ETH_Byte_1</td><td>ETH_Byte_0</td></tr>
<tr><td></td><td></td><td colspan="4">…</td></tr>
<tr><td>word M</td><td></td><td>Zero_Pad</td><td>Zero_Pad</td><td>ETH_Byte_n-1</td><td>ETH_Byte_n-2</td></tr>
</table>

The implementation shall be capable of emitting FSO frames with partially packed Ethernet frames. In the case that the Ethernet frame is segmented, the Ethernet bytes are continued into the immediately following FSO DATA frame with the appropriate signaling in the FSO Payload header as previously described (Section 2.6.3.7.5).

Every FSO frame shall end with a 32-bit CRC as illustrated in Figure 2-10. In all cases, the CRC shall cover the entire frame, including any portions of the frame padded with zeros.

2.6.3.7.7 Reassembly of Ethernet Frames

The implementation's optical RX PHY shall reconstruct the sequence of ingress Ethernet packets from the (packed) FSO frames received from the far-end terminal. The frames shall be transmitted on its egress Ethernet in the same order and with the same packet sizes as received by the Ethernet RX PHY on its ingress Ethernet.

The Reassembly process (the Reassembly Block in Figure 2-16) shall implement the following:

- If an FSO frame is received with a sequence number skip, any Ethernet packet whose payload was not complete shall be discarded. The received FSO frame with the skipped sequence number shall be retained only if the length field of its FSO frame header is zero. Any FSO packet headers following the end of the first partial packet in the FSO frame are valid.
- Any FSO frame whose magic number in its FSO Frame Header (Table 2-18) is incorrect shall be discarded entirely.
- Any FSO Packet Header within any FSO frame (Table 2-18) whose magic number is incorrect shall be discarded.
- Any FSO Packet Header whose length field is inconsistent shall be discarded.

2.6.3.7.8 Ranging and Position, Navigation, and Timing (PNT)

2.6.3.7.8.1 Time Stamping

The TX PHY shall timestamp each FSO frame consistent with the technique described in Section 2.6.3.3.4. The timestamp shall reference the rising edge of the first bit of the optical frame. The timestamp shall be accurate to within 10 nanoseconds relative to the local bus 10 MHz reference clock.

The RX PHY shall record a timestamp and sequence number of the incoming frame at a frequency of at least 1 Hz. The rate of time stamp recording should be remotely controllable and reportable.

The implementation shall reference the recorded timestamp to the ingress time of the rising edge of the first bit of the modem frame. The implementation shall compensate timestamps (as required) for systematic time delays due to propagation paths outside the over-the-air connection between a pair of terminals. The means for calibrating path delays and compensating timestamps shall be implementation dependent.

2.6.3.7.8.2 Ranging Data: Two-way Frame Timestamps and Range

The receiving OISL shall, at a frequency of at least one hertz but no greater than the rate specified in Section 2.6.3.7.8.1, provide timestamp data back to the transmitting OISL. This data shall be sent in a MGMT frame as described in Table 2-9. The Timestamp Frequency should be commanded by the requesting OISL and, when commanded, shall be communicated as a positive number corresponding to the Timestamp Frequency.

The payload of a ranging response frame shall contain the following data:

- The egress timestamp of the frame which was measured on receipt
- The ingress timestamp of the measured frame

The payload of a ranging response frame should contain the following data:

- Time-tagged ranging measurements accurate to < 3 meters

In addition to these data, the egress timestamp of the management frame shall be collected by the terminal receiving the management frame. As outlined in Table 2-9, this timestamp shall occur either in the MGMT frame or in the subsequent frame as indicated by the timestamp location flag.

The space segment should provide the above time-tagged ranging measurements to <10 ns relative to the SV clock to the ground, to the onboard processing (e.g. BMC3), and to the bus to be provided to TT&C subscribers. See [5] for time and frequency terms including range.

3 Glossary

Baud Rate

Baud time is defined as the signaling time required to transmit a single coded frame bit and shall include all sources of overhead including line code, preamble, header, cyclic redundancy checks (CRCs) and forward error correction (FEC). Baud rate, expressed in Hz, is the inverse of baud time.

Data and Symbol Rates

Data and symbol rates are expressed as bits-per-second (bps) and symbols-per-second (baud). Bps is defined as 1 bit/second. Similarly, baud is defined as 1 symbol/sec. SI-prefixes for these rates are expressed in base-10 and not in base-2. For example, 100 Mbps represents 100 x 10^6 bps or 10^8 bps.

Bit Numbering Convention

The convention used to identify each bit in an N-bit field will conform to Section 1.6.3 in [6].

Field of View (FOV)

The field of view is the solid angle that represents the instantaneous viewing angle of the sensor. Multiple FOVs may be defined for a sensor and shall be specified in-line sufficiently to indicate the applicable geometry. For example, the system may have different FOVs for the communications, acquisition, and tracking channels. These three FOVs may be specified as the Communications Channel FOV, Acquisition FOV, and Tracking FOV.

Field of Regard (FOR)

The field of regard is the total the solid angle defined by the allowable motion of the sensor combined with the field of view. The FOR shall, by default, refer to the terminal's FOR.

Solid Angle

The angles defining the sensor, including, FOV and FOR, shall be expressed as a solid angle, typically specified in steradians, square degrees, or square radians.

Alternatively, and perhaps more commonly, the solid angle of the sensor may be expressed in degrees, which shall be taken to be mean, by default, the solid angle defined by equal apex angles of a pyramid's intersection with a sphere, which defines a spherical cap on a unit sphere. This represents a square sensor's projection onto a sphere. Deviations of this pyramidal definition are permitted, the most common being a conical approximation, however such deviations shall be explicitly annotated.

Extinction Ratio

Extinction ratio is the ratio of two optical power levels of a signal generated by an optical source.

Polarization Extinction Ratio (PER)

Ratio of optical powers for perpendicular polarizations.

Irradiance

Irradiance is the radiant flux received by a surface per unit area. The SI unit for irradiance is the watt per square meter (W/m^2).

Radiance

Radiance is the radiant flux transmitted, emitted, or received by a given surface per unit solid angle. The SI unit for radiance is the watt per square meter per (W/m2/per steradian).

Line Product Code (LPC)

Line Product Code is coding technique to the optical transmitter will remain within the safe operating envelope of the optical amplifier by minimizing the difference between the number of transmitted ones and zeros, called disparity. The Line Product Code may also be used to produce a tracking tone.

Part Per Million (PPM)

A measurement used to quantify deviation from nominal value.

Amplitude Modulation (AM)

Amplitude modulation (AM) is a modulation technique used in electronic communication. In amplitude modulation, the amplitude (signal strength) of the carrier wave is varied in proportion to that of the message signal.

Modulation Index (MI)

Modulation index is a measure based on the ratio of the modulation excursions of a signal to the level of the unmodulated carrier.

Coded Bit-Error Rate

The number of bit errors per unit time prior to applying Forward Error Correction.

Decoded Bit-Error Rate

The number of bit errors per unit time after applying Forward Error Correction.

Packet Error Rate

The ratio of number of Ethernet packets received in error to total number of transmitted Ethernet packets.

Pseudo-Random Binary Sequence

A pseudorandom binary sequence (PRBS) is a binary sequence that, while generated with a deterministic algorithm, is difficult to predict and exhibits statistical behavior similar to a truly random sequence.

4 References

The following publications contain provisions that, 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 document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below.

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

[2] CCSDS, *CCSDS Orange Book 141.11-O-1 Optical High Data Rate (HDR) Communication,* CCSDS, 2018.

[3] ITU-T, *ITU-T Recommendation G.694.1 Spectral grids for WDM applications: DWDM frequency grid,* 2020.

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

[5] ITU, *ITU-T Recommendation TF.686-3 Glossary and definitions of time and frequency terms.,* 2013.

[6] CCSDS, *CCSDS 133.0.P-1.1 SPACE PACKETPROTOCOL,* 2019.