DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

SDA Tranche 1 Optical Communications Terminal Standard

Developed by the

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This document is a DRAFT Standard and is subject to change.

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1. Introduction

The purpose of this document is to provide the framework and protocol definitions for optical communications systems employed by the Space Development Agency (SDA) and its partners. The scope of optical communication links supported includes space-to-space (S2S, a.k.a. Optical Intersatellite Links or OISLs), space-to-air (S2A), space-to-maritime (S2M), and space-to-ground (S2G) optical communications.

The SDA OISL Standard [1] was first published in early 2020 [2] in preparation for the first iteration of the SDA spiral development process: Tranche 0. SDA's Tranche 0 (T0) program added sufficient detail to the initial OISL Standard as to enable demonstration of multi-vendor interoperability. Since early 2020, significant advancements have been made across the Optical Communications Terminal (OCT) market. These advancements have prompted the addition of several protocols to the OISL Standard.

The document has been renamed the Optical Communications Terminal (OCT) Standard due to its applicability to S2G, S2M, and S2A links. This scope, being broader than ISLs alone, prompted the change.

This OCT Standard (the Standard) is intended to enable interoperability between optical communications where at least one endpoint is a space-based terminal.

1.1. Elements of the OCT Standard

This document provides descriptions of the Physical Layer and Synchronization and Channel Coding Sublayers as described by CCSDS. These correspond to Layer 1 and a portion of Layer 2 of the OSI Model, respectively. This document specifies the OCT to OCT interface.

The Physical Layer is the lowest layer. For the case of the OCT, the physical layer describes the laser parameters (e.g. wavelength, channel spacing, and spectral width) and the modulation parameters (e.g. OOK-NRZ or M-ary PPM). This section includes specifications of the user data rate, which, due to overhead from higher layers (e.g. from frame headers, error correction, etc.), is less than the user line rate.

In addition, unlike optical fiber, which provides a guided transmission medium between modems, free-space optical communications (FSOC) terminals must be spatially co-aligned. This requires the systems to accurately locate the remote terminal at range and point at the remote terminal with an accuracy sufficient to capture its signal. This acquisition process must be synchronous. In this Standard, real-time communications do not occur prior to establishment of the FSOC channel. This requires that the acquisition processes on the pair of terminals be both well-choreographed and synchronized to a common clock. This choreography is governed by the state machine (described in Section PAT State Machine) and its associated parameters.

For systems in motion, such as the OCTs used on spacecraft and aircraft, the systems must each track their remote counterpart in order to maintain alignment. This motion includes the general flight path of the host platform as well as the jitter imparted by the platform. OCTs, whose receivers typically have relatively small fields-of-view (FOV), must compensate for this lower-rate motion and higher-rate jitter. This is accomplished through a closed-loop tracking system which uses the remote signal as the measurement reference. Corrections are fed to a coarse tracking apparatus (e.g. a gimbal) to correct the lower-rate motion and a fast tracking apparatus (e.g. a Fast Steering Mirror (FSM) to correct the higher-rate jitter.

The Synchronization and Channel Coding layer, which corresponds to the “lower” part of the OSI Model’s Layer 2 (see [3]), defines the tools necessary to permit largely error-free transmission (e.g. Forward Error Correction (FEC), scrambling, and line codes) as well as the structure of the data (e.g. framing).

1.2. Requirements

Requirements in this document take two forms:

1. Normative text indicating ‘shall’ or ‘must’
2. Enumerated Requirements, which will typically include normative text. These are specifically labeled for reference.

Enumerated requirements are assigned an ID and explicitly stated in this Standard in the following format:

Requirement OCT-<NNN>: <Requirement Description>

1.3. Normative Text

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

a. the words ‘shall’ and ‘must’ indicate a **binding and verifiable** specification

b. the word ‘should’ indicates an **optional, but desirable**, specification

c. the word ‘may’ indicates an **optional** specification

d. the words ‘is’, ‘are’, and ‘will’ indicate **statements of fact**

1.4. Definitions

Term	Definition
Line Rate	The gross bitrate of the physical layer of a communications channel. *Line Rate* may also be referred to as the “raw bitrate,” “data signaling rate,” “gross data transfer rate,” or “uncoded transmission rate.” [4]
Bitrate	The number of bits conveyed per unit of time.
Line Code	A pattern of voltage, current, or photons used to represent digital data transmitted down a transmission line. [4]

User Rate	The net bitrate of the communications channel. This is exclusive of protocol overhead (e.g. FEC). User Rate may also be referred to as the “payload rate” or “effective data rate.” The *User Rate* is always less than or equal to the *Channel Capacity*. [4]
Channel Capacity	The theoretical upper bound for the maximum net bitrate, exclusive of forward error correction coding, that is possible without bit errors for a certain physical analog node-to-node communication link. *Channel capacity* may also be referred to as the “Shannon Capacity.” [4]
Modulation	Modulation is the process of varying one or more properties of a periodic waveform, called the carrier signal, with a separate signal called the modulation signal that typically contains information to be transmitted. [4]
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.
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.
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).
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/m2).
Polarization Extinction Ratio (PER)	Ratio of optical powers for perpendicular polarizations.
Extinction Ratio	Extinction ratio is the ratio of two optical power levels of a signal generated by an optical source.
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 means, 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 must be explicitly annotated.
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, by default, refers to the terminal’s FOR.
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 is 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.
Bit Numbering Convention	The convention used to identify each bit in an N-bit field will conform to Section 1.7 in (1).
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.
Baud Rate	Baud time is defined as the signaling time required to transmit a single coded frame bit and includes 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.
Part Per Million (PPM)	A measurement used to quantify deviation from nominal value.
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 prior to applying Forward Error Correction.
Packet Error Rate	The ratio of number of Ethernet packets received in error to total number of transmitted Ethernet packets.

1.5. Table of Acronyms

Acronym	Meaning
ACK	Acknowledgement
AM	Amplitude Modulation
ANSI	American National Standards Institute
ARQ	Automatic Repeat Request
BER	Bit-Error Rate
CCSDS	Consultative Committee for Space Data Systems
CRC-16	Cyclic Redundancy Check with a 17-bit polynomial.
DCE	Data Circuit-terminating Equipment
DTE	Data Terminal Equipment
DWDM	Dense WDM
FCCH	Fast Communications Channel
FEC	Forward Error Correction
FOV	Field of View

HDR	High Data Rate
ICD	Interface Control Document
IEEE	Institute of Electrical and Electronics Engineers
IFOV	Instantaneous Field of View
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
MI	Modulation Index
OCT	Optical Communications Terminal
OGT	Optical Ground Terminal
OISL	Optical Inter-satellite Link
OOK	On-Off Keying
OOK-NRZ	On-Off Keying Non Return-to-Zero
OSI	Open Systems Interconnection
PPM	Pulse Position Modulation
PPM	Parts Per Million
PRBS	Pseudo-Random Bit Sequence
PRBS	Pseudo-random Binary Sequence
S2A	Space-to-Air
S2G	Space-to-Ground
S2M	Space-to-Maritime
S2S	Space-to-Space
S2T	Space-to-Terrestrial
SDA	Space Development Agency
T0	Tranche 0
T1	Tranche 1
T2	Tranche 2
WDM	Wavelength-division Multiplexing

2. Layer 1 - Physical Layer

The Physical Layer as presented below corresponds to the Physical Layer as used in the OSI Model and in an equivalent manner by the CCSDS Model. This layer corresponds to the lowest layer in both models.

The Physical Layer defines the transmission and reception of unstructured data between two OCTs. In this case, a diverging optical signal is transmitted through the vacuum of LEO space for S2S links and through a turbulent atmosphere for S2T links. The atmosphere affects FSOC links in two ways:

1. T atmosphere absorbs a portion of the light, resulting in a range-dependent attenuation of the signal
2. Turbulent flow of the atmosphere modifies the wave-front and has several effects resulting in
    a. Scintillation: variations in the signal intensity (and thereby the SNR), color, and position
    b. Time-varying phase imparted on the signal

Other atmospheric effects, such as weather, are included as part of the physical layer. These effects primarily result in reduction of throughput. This reduced performance is handled through application of CONOPS designed to minimize the impact on system performance.

The physical layer is separated into two channels:

1. Pointing, Acquisition, and Tracking (PAT)
2. Communications

The PAT channel's purpose is to provide the required signals and motion control to align two terminals in order to establish a communications link. The communications channel provides the transmission and receipt of an optical signal with specified parameters, such as wavelength and modulation, required to transport information from the local to remote terminal

2.1. Pointing, Acquisition, and Tracking (PAT)

The spatial acquisition strategy used by this Standard follows the spatial acquisition sequence described in Section 2.3 of the CCSDS Orange Book *OPTICAL HIGH DATA RATE (HDR) COMMUNICATION—1064 NM* [3]. This beaconless PAT procedure employs a time-tagged sequence of search activities. Temporal synchronization is necessary due to the lack of a side-channel for coordination of the acquisition sequence. The procedure is successful once the terminals are spatially aligned.

The spatial acquisition sequence, referred to as the Pointing, Acquisition, and Tracking sequence follows the PAT State Machine defined in 2.2.2State Machine

2.2. PAT State Machine

2.2.1. States

1. Not Ready
2. Idle
3. Acquisition
4. Tracking

2.2.2. State Machine

The PAT State Machine defines the states used for command and control of the OCT's PAT process. It is shown in Figure 1. PAT State Machine below.

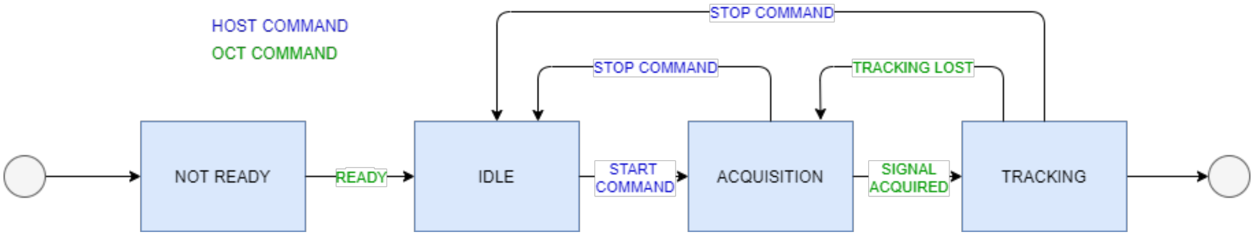

Figure 1. PAT State Machine. Note: the implied transition on ERROR EVENT from any state to NOT READY is implied.

Note: On an ERROR EVENT, the system shall revert to the NOT READY state. This transition is implied and not directly depicted in the state machine diagram or state machine transition table (Table 2. State Transition Matrix).

Note: No exit route is explicitly defined.

2.2.3. State Transition Signals

The state transition signals are defined in Table 1. State Transition Signals.

Table 1. State Transition Signals

Signal	Description
READY	The ready signal indicates that the OCT has completed all required actions (e.g. boot up, initialization, etc.) required to be ready to await the command to establish a link.
START COMMAND	The START COMMAND signal is a command from the Host that indicates that all required parameters are in place and PAT should begin.
STOP COMMAND	The STOP COMMAND signal is a command from the Host that indicates that the system should cease all link actions and shut down the link
SIGNAL ACQUIRED	This signal indicates that the signal has been acquired and the system is (or has) moved on to closed-loop tracking.

TRACKING LOST	This signal indicates that the remote signal has been lost for longer than the time defined by the Tracking Lost Timeout parameter. The period between loss of track and TRACKING TIMEOUT is the Tracking Coast Period.
ERROR EVENT	This signal, not shown in the State Transition Criteria Matrix and not depicted in the PAT State Machine Diagram, indicates an unexpected error (e.g. a software exception). The state reverts to NOT READY

2.2.4. State Transition Criteria Matrix

The matrix shown in Table 2. State Transition Matrix describes the state transition (denoted: State -> <New State>) in response to the signals defined in 2.2.3State Transition Signals.

Table 2. State Transition Matrix

		State			
		NOT READY	IDLE	ACQUISITION	TRACKING
Signal	READY	IDLE	Ignored	Ignored	Ignored
	START COMMAND	Ignored	ACQUISITION	Ignored	Ignored
	STOP COMMAND	Ignored	Ignored	IDLE	IDLE
	SIGNAL ACUIRED	Ignored	Ignored	TRACKING	Ignored
	SIGNAL LOST	Ignored	Ignored	Ignored	ACQUISITION

2.2.5. Host Commands

Requirement OCT-001: The OCT shall permit the Host to command state changes. Commands shall override the state transition rules shown above.

Requirement OCT-002: Exit from the NOT READY state shall require command from the Host.

Note: The NOT READY state may be entered through both OCT startup and upon an ERROR EVENT.

2.2.6. ACQUISITION State

The ACQUISITION State includes all acquisition activities including execution of the spatial acquisition process. The spatial acquisition process starts upon entry to this state.

The Host provides parameters along with the signal that specify the scan to be performed. The scan is executed and ends when one of the following conditions are met:

1. The remote signal is acquired, resulting in a SIGNAL ACQUIRED signal
2. The STOP COMMAND is received from the Host

When one full scan is completed without successful acquisition of the remote signal, the scan is repeated until the STOP COMMAND is received from the Host.

Two scan routines are defined in this Standard:

1. Simultaneous Spiral Scan

2. Nested Spiral Scan

The Simultaneous Spiral Scan is used for geometries with low pointing uncertainty whereas the Nested Spiral Scan can be configured as an exhaustive search and is employed when the uncertainties are high. The scan method shall be directed by the Host. The scan patterns are defined in 2.2.6.1 and the required theory and equations are provided in Appendix A: Spiral Scan Definition (Section 5).

2.2.6.1. Acquisition Search Pattern

The acquisition process shall employ two scan types:

1. Spiral Scan: Both OCTs executes constant-velocity Archimedean spiral scans as defined in Appendix A: Spiral Scan Definition (Section 5).
2. Nested Spiral Scan: One OCT is commanded to execute a stepped Archimedean spiral scan as defined in Appendix A: Spiral Scan Definition (Section 5). The other OCT is commanded to execute a constant-velocity Archimedean spiral scan as defined in Appendix A: Spiral Scan Definition (Section 5)a. *The start time is identical for both OCTs.*

2.2.7. ACQUISITION State Activities

Requirement OCT-003: Upon entry into the ACQUISITION state, the OCT shall perform a scan and provide a SIGNAL ACQUIRED signal upon successful acquisition of the remote terminal's signal.

The scan to be performed will be a spiral-form scan as described in Appendix A (Section 5). Two scan types are allowed. The first is a Spiral Scan and the second is a Nested Spiral Scan. The parameters required for each scan are as follows:

Table 3. Acquisition Parameters

Parameter	Notes
Scan Type	This parameter indicates the type of scan. The values may be *Spiral* or *Nested Spiral*.
$\boldsymbol{\Gamma_{scan}}$	This is the cone angle to be scanned.
$\boldsymbol{\eta_{scan}}$	This is the "spacing" between successive loops of the spiral.
$\boldsymbol{t_{scan}}$	The scan duration in time.
$\boldsymbol{\eta_{step}}$	For Nested Spiral Scans, this is the step size of the outer-loop scan.
$\boldsymbol{t_{step}}$	For Nested Spiral Scans, this is the slew and settle time allotted to each step.

Note: $\eta_{step}$and t_{step} are required for the Nested Spiral Scan only.

2.2.8. Acquisition Signal

The acquisition signal is defined as an amplitude modulation (AM) on the transmitted signal at a lower frequency than the data signal. The nominal AM Tracking Tone Modulation Index (MI) is defined as:

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

Requirement OCT-004: The OCT shall provide an amplitude modulation (AM) *Acquisition Signal*.

Requirement OCT-005: The OCT shall reference the amplitude of the *Acquisition Signal* to the minimum and maximum amplitude of the transmitted signal to the Modulation Index (MI).

Requirement OCT-006: The OCT's *Acquisition Signal* shall be a sinusoid. The *Sinusoidal Tone* is a sine wave modulation at a specified frequency.

2.2.9. PAT Acquisition Time

The acquisition time is the time between the START COMMAND signal and the successful spatial alignment such that the link is "established." The link is established when the OCT is tracking and data are being transported across the link.

C*old start* means the post-calibration acquisition of a remote terminal that has not yet been acquired.

Warm start means the post-calibration acquisition of a remote terminal that has been recently tracked by the OCT.

Recently, in this context, shall refer to the period of time for which the error in a recent *Tracking Pointing Vector* results in a *Warm Start Uncertainty Cone.*

Examples:

1. For a spacecraft, a *warm start* is the period since the last successful track for which there has been no maneuver by either the local or remote spacecraft and the propagation error of the Tracking Pointing Vector is sufficiently low so as to enable a significantly more rapid acquisition, typically improved by one or more orders-of-magnitude in acquisition time, when compared to a cold start.
2. For a spacecraft to aircraft, a cold start results when the trajectory of the aircraft changed since the Tracking Pointing Vector Epoch.

2.3. Modulation

Requirement OCT-007: The OCT shall support On-Off-Keying Non-Return-to-Zero (OOK-NRZ).

Requirement OCT-008: The OCT shall support M-Ary PPM (MPPM) for M ∈ {4, 8, 16, and 32} per CCSDS 142.0-B-1 [5].

2.4. Latency

The Receive Latency is defined as the duration of time from the first photon of a message arriving at the OCT to the last bit of that message exiting the OCT to the host spacecraft.

The Transmit Latency is defined as the time between delivery of the first Ethernet packet from the host spacecraft to the OCT and the transmission of the last packet to exit the plane of the aperture of the OCT.

2.5. Spectral Grid Definition

To permit operations of multiple communications channels through wavelength division multiplexing (WDM), the ITU-T G.694 [6] 100 Ghz channel will serve as the basis for SDA Optical Communications channels. This grid follows the ITU-T G.694.1 recommendation and is limited to the 44 channels in the optical C-Band (1530 nm to 1565 nm).

$$F_{Center}(\mathrm{n}) = 193.1\ THz + n \times 100\ GHz$$

2.6. Transmit and Receive Wavelength

Table 4defines the transmit and receive wavelengths. Either channel may be used for send while the other is used for receive. The same channel may not be used simultaneously for send and receive.

Table 4. Channel definitions.

Channel Number (n)	Frequency (THz)	Wavelength (nm)	Transceiver	Codec	User Data Rate (Gbps)
-1	193.1	1553.33	Direct Detect OOK-NRZ or M-ary PPM	SDA-2021A	$0.25 \le x \le 2.5$
20	195.1	1536.61	Direct Detect OOK-NRZ or M-ary PPM	SDA-2021A	$0.25 \le x \le 2.5$

2.7. Channel Selection

Requirement OCT-009: The Host shall be able to select the OCT's transmit and receive wavelengths through software set and get commands.

2.8. Polarization

Requirement OCT-010: The OCT shall transmit Left-hand Circular Polarization (LHCP) optical signals, where the E-vector rotates counter-clockwise as viewed from the transmitter in the direction of propagation per [5].

Requirement OCT-011: OCTs shall receive signals from LCHP-transmitters.

Requirement OCT-012: The OCT's irradiance levels shall be measured in the LHCP polarization state in the direction of propagation from transmitter to receiver.

Requirement OCT-013: The transmitter shall emit LHCP light with a tolerance of 23 dB or higher.

Requirement OCT-014: The transmitter shall provide an irradiance at the plane of the receive aperture at a range of 7500 km of up to $30\ \mu W/m^2$.

3. Layer 2 - Synchronization and Channel Coding Layer

3.1. Protocols

SDA intends to leverage the availability of commercial off-the-shelf (COTS) components and intellectual property (IP).

Table 5 defines the protocol names, ID, and modulation type. These protocols are described in this section. The protocol class is referred to as the *SDA-LDPC*.

Table 5

Protocol	Protocol ID	Modulation
2021A-OOK-NRZ-LDPC	SDA-2021A	OOK-NRZ
2021B-M-PPM-LDPC	SDA-2021B	M-Ary PPM

Requirement OCT-015: The OCT shall implement the SDA-2021A and SDA-2021B Protocols.

3.2. Re-Programming

Requirement OCT-016: Layers 1 and 2 shall be re-programmable. During reprogramming, the transmission of data may be interrupted.

3.3. Effective Data Rate and Protocols

Protocols and the applicable data rates are shown in Table 6.

Note: The data rates are approximate and are defined in the associated reference documents.

Table 6

Protocol ID and Rate Designator (format: <Protocol ID>-<Rate ID>)	User Data Rate
SDA-2021A-0	78.125 Mbps
SDA-2021A-1	156.25 Mbps
SDA-2021A-2	312.5 Mbps
SDA-2021A-3	625 Mbps
SDA-2021A-4	1.25 Gbps
SDA-2021A-5	2.5 Gbps
SDA-2021B-0	78.125 Mbps
SDA-2021B-1	156.25 Mbps
SDA-2021B-2	312.5 Mbps
SDA-2021B-3	625 Mbps
SDA-2021B-4	1.25 Gbps
SDA-2021B-5	2.5 Gbps

Requirement OCT-017: The OCT shall be capable of transmitting and receiving in full duplex at the user data rates defined in Table 6.

3.4. Framing, Coding, and Encapsulation

3.4.1. Frame Structure

The structure of the OTA frames used by the OCT modem is shown in Table 7.

Requirement OCT-018: All OTA frames in the OCT modem shall be constructed identically: a preamble sequence concatenated with a fixed-length header followed by data bits (fixed size, plus CRC) then a variable number of parity bits. The number of parity bits is governed by the configured codec and code rate (Section 3.4.3.1).

Table 7: Modem Frame Format

Field	# of bits	Comments
Preamble	64	Preamble: 64'53225b1d0d73df03. The MSB (64th) bit is transmitted first followed in order down to the LSB (1st).
Header	948	See Section 3.4.1.2.
Payload - Data	8160	Information payload. Fixed size (8160 bits) for all modem frame configurations.
Payload - CRC	32	Cyclic redundancy check covering payload bits.
Payload - Parity	variable	Number of parity bits depends on the configured payload FEC codec and code rate.

Requirement OCT-019: 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 7.

3.4.1.1. Preamble Sequence

Requirement OCT-020: Every frame shall start with a Preamble Sequence (PS), which is used by the receive modem for frame synchronization.

Requirement OCT-021: The preamble sequence shall be identical for all OCT modem frames and takes the value shown in Table 7.

3.4.1.2. Header

Requirement OCT-022: A modem header shall be present in every modem frame immediately following the preamble sequence.

Requirement OCT-023: The OCT modem frame header shall have these characteristics:

- Modem headers are a fixed size (i.e., number of coded bits) for all configurations.

- Modem headers are protected by a strong Forward Error Correction (FEC) scheme with a fixed code rate (Section 3.4.2.2)
- The payload of the modem header is protected by a CRC-16 (Section 3.4.2.1).

The contents of the OCT modem frame header are detailed in Section 3.4.3.

3.4.1.3. Payload

This section describes how payload (information) bits are encoded into the OCT modem frame.

3.4.1.3.1. Data Bits

Requirement OCT-024: All modem frames shall carry a payload of exactly 8160 information bits.

3.4.1.3.2. CRC-32

Requirement OCT-025: All modem frames shall protect the integrity of the payload information bits with a 32-bit CRC (Section 3.4.2.1).

3.4.1.3.3. Parity Bits

The OCT modem features strong payload FEC.

Requirement OCT-026: The payload shall implement FEC with the following properties:

- Systematic FEC (i.e., a copy of the payload data bits appears in the encoded payload codeword).
- Zero or more parity bits.

  The number of parity bits is a function of the codec and code rate selection (Table 10) and can be as few as zero bits (uncoded) up to as many as 8192 bits (LDPC, code rate 1/2).

  The payload FEC is a systematic, irregular low-density parity check (LDPC) code with a weight-one circulant structure and circulant size of 64.

3.4.1.4. Scrambling

Requirement OCT-027: All portions of the modem frame, except for the Preamble Sequence, shall be scrambled prior to transmission as described herein.

The scrambling sequence is a maximal length sequence (equivalently referred to as an m-sequence) generated by the primitive polynomial

$$p(x) = 1 + x^{14} + x^{15}.$$

The sequence can be generated by a linear-feedback shift-register circuit. A reference implementation producing the correct scrambling sequence is shown in Figure 2. The following describe the sequence employed in the generation of the scrambling sequence:

- The shift-register is initialized to $[x_0, x_1, \ldots, x_{14}] = [000011011011100]$ at the start of every frame.

- The shift register circuit is clocked once per transmitted bit for the totality of the frame. However, scrambling is not applied to the Preamble Sequence (initial 64 bits of the frame). Beginning with the first bit *after* the Preamble Sequence, frame bits f_k are exclusive-or with the scrambling sequence s_k.
- Scrambled sequence $y_k = f_k + s_k$ is transmitted over the air, where "addition" is over GF(2). Binary addition on GF(2) is mathematically equivalent to an exclusive OR (XOR) operation.

The circuit shown in Figure 2 generates a scrambling sequence with period $2^{15} - 1 = 32767$ bits.

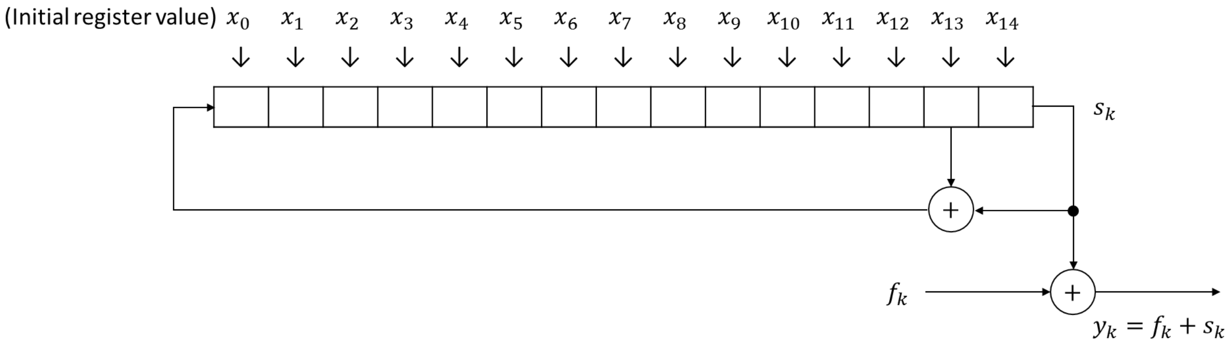

Figure 2: Generation of Scrambling Sequence

The modem starts preamble sequence generation at the first bit of the frame with the first 64 bits of the preamble sequence not applied (these cover the preamble sequence, which is not scrambled).

The same scrambling seed is applied at the start of every modem frame.

Figure 3 depicts the steps for frame generation.

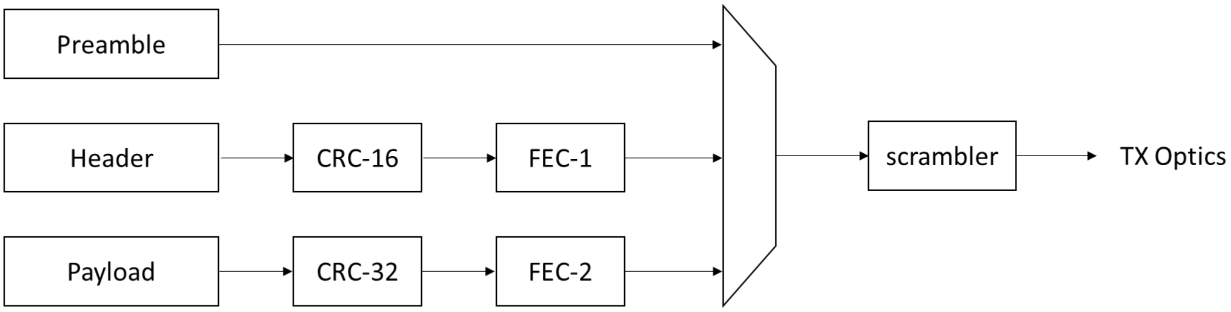

Figure 3: OCT modem Frame Construction

All frame types (Section 3.4.4) are constructed identically.

3.4.2. Error Control Coding

Requirement OCT-028: All OCT modem frames shall feature strong error control coding as described herein.

The error control coding features the following:

- Information bits are protected by CRC's (Section 3.4.2.1, header: 16 bits, payload: 32 bits)
- Fixed-rate convolutional code (CC) for the frame Header (Section 3.4.2.2)
- Variable-rate low-density parity check code (LDPC) for the frame Payload (Section 3.4.2.3).

This section details the encoders for all the error control codes.

3.4.2.1. CRC

Two CRC's are required to generate the modem frame: a CRC-16 protects the Header while a CRC-32 protects the payload. A functional description of a generic L-bit CRC encoder circuit is shown in Figure 4. 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 8 for each of the two CRC's required to create the modem frame.

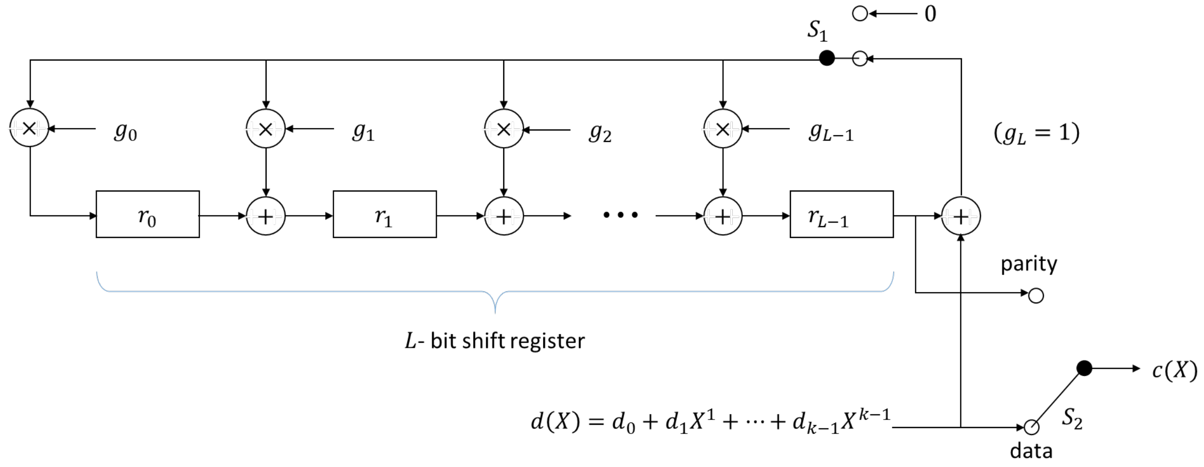

Figure 4: L-bit CRC Calculation Circuit

Calculation of the CRC for a block of k payload bits:

- 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.

Table 8: CRC Polynomials

Location	Length	Polynomial	Source
Frame Header	16 bits	$g(x) = x^{16} + x^{12} + x^5 + 1$	CCITT X.25

Frame Payload	32 bits	$g(x) = x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$	ANSI, IEEE 802.3, ITU-T V.42

3.4.2.2. *Header FEC*

The modem header payload is encoded by a non-systematic constraint length 7, rate 1/6 convolutional code prior to transmission. Generator polynomials for this (7, 1/6) code are listed in Table 9.

Table 9: Rate 1/6 Convolutional Code for Frame Header

Coded bit	Generator Polynomial (octal)
0	0175
1	0171
2	0151
3	0133
4	0127
5	0117

The convolutional encoder is initialized at the start of every new Header to state zero. Header payload enters the encoder MSB first up to the end of the 16-bit CRC then flushed with 8 zero-valued bits to return the encoder state to zero.

The total size of the encoded header as transmitted “over the air” is $158 \times 6 = 948$ bits.

3.4.2.3. *Payload FEC*

All OCT modem frames carry an 8160-bit payload per frame which is protected by both a CRC-32 and by variable code rate strong FEC. This includes:

- Low-Density Parity Check Code (LDPC)
- Systematic Encoder
- Variable code rate from $R = \frac{8}{9}$ to $R = \frac{1}{2}$.

To facilitate efficient implementation of the LDPC codec on FPGA platforms the LDPC code is designed with these structural properties:

- Single weight circulant structure
- Circulant size 64
- Irregular

Circulant tables describing the LPDC code are in Section 3.5.

3.4.3. Frame Header

This section details the contents of the OCT modem header. The modem header implements the signaling required for implementation of the modem features.

3.4.3.1. Header Fields

The frame Header fields are listed in Table 10. A single Header is present in every modem frame.

Table 10: Frame Header Fields

Function	Field	Bits	Description
ARQ	TXFN	16	Sequence number of this (outgoing) TX frame
	ACK_START_FN	16	Sequence number of first ACK
	ACK_SPAN	3	ACK/NAK applies to 2^(ACK_SPAN) consecutive RXFN
			000-101: legal values (ACK_SPAN=1, … ACK_SPAN=32)
			110-111: Reserved
	ACK_valid	1	0: no ACK/NAK in this frame
			1: ACK/NAK valid
	ACK	1	0: NAK for RXFN and 2^(ACK_SPAN) consecutive RXFN
			1: ACK for RXFN and 2^(ACK_SPAN) consecutive RXFN
	TX_NUM	3	transmission attempt (0=initial, max re-TX=7)
FEC	PL_RATE	2	0: 1024 parity bits
			1: 2048 parity bits
			2: 4096 parity bits
			3: 8192 parity bits
MAC	FRAME_TYPE	2	0: IDLE
			1: DATA
			2: MGMT
			3: reserved
pseudo-range	TX_TS	40	TX time-stamp (frame egress)
Fast Control Channel	FCCH_OPCODE	4	time-multiplexed control signalling
	FCCH_PL	48	Payload contents depends on FCCH_TYPE
CRC	CRC-16	16	
Zero-tail	ZT	6	Flush convolutional code state to zero
Total		158	

3.4.3.2. Automatic Repeat Request (ARQ)

Header fields supporting implementation of the Automatic Repeat Request modem feature are grouped as the “ARQ” fields in Table 10. The ARQ configuration parameters shall remain static for the duration of a session. The ARQ configuration may only be changed prior to the onset of acquisition. ARQ operation is not expected to be used for crosslinks. More details can be provided if needed.

3.4.3.3. Payload FEC

The OCT modem features strong payload FEC (Section 3.4.2.3).

The payload FEC code rate is computed $R = 8192/(8192 + \mathrm{nparity}))$. Payload code rates are tabulated in Table 11.

Table 11: Payload FEC Code Rates (LDPC)

PL_RATE	Number of parity bits	Payload Code Rate (LDPC)
0	1024	8/9
1	2048	4/5
2	4096	2/3
3	8192	1/2

3.4.3.4. Range Measurement

Requirement OCT-029: The OCT modem shall provide an integrated ranging capability when enabled.

3.4.3.4.1. Timestamps

Requirement OCT-030: The TX PHY shall apply a timestamp in the header of every modem frame (TX_TS field, Table 10). The implementation shall reference the applied timestamp to the egress point of the modem frame (crossing the plane of the aperture).

Requirement OCT-031: The RX PHY shall similarly record a timestamp of the ingress of every modem frame (RX_TS). The implementation shall reference the recorded timestamp to the ingress point of the modem frame (crossing the plane of the aperture).

3.4.3.5. Fast Control Channel (FCCH)

Requirement OCT-032: The OCT modem frame shall provide an embedded fast control channel (FCCH) as described herein.

The FCCH provides a low-rate channel with reserved bandwidth for robust, low-latency transport of short messages between OCT terminals. The FCCH enjoys the benefit of both error detection (via the Header CRC) and strong 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 is time-multiplexed:

- FCCH_OPCODE (4 bits): opcode which determines the format of the FCCH payload
- FCCH_PL (48 bits): payload bits.

A single FCCH is transmitted and received in every frame and can be valid for every FRAME_TYPE (Table 10 and Section 3.4.4).

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 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 ones. Payload values for Reserved opcodes must be all zeros.

New types of FCCH can be defined as needed. Details of the FCCH messages can be provided.

Table 12: FCCH Logical Channels

Description	FCCH _TYPE	Opcode (4 bits)	Payload
Capabilities	OCT_CAPABILITIES	0000	
Link Adaptation	LAPC_REPORT	0001	
Reserved	N/A	0011-1110	N/A
Not Present	N/A	1111	

3.4.4. Special Frames

Requirement OCT-033: The FRAME_TYPE field of the frame Header (Table 10) shall signal the type of modem frame as described herein.

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.

3.4.4.1. 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.

3.4.4.1.1. Header Construction

Modem IDLE frames are signaled in the frame header by field FRAME_TYPE=00 (Table 10).

Modem IDLE frame headers are 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.

3.4.4.1.2. Payload Construction

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

The information payload in IDLE frames is constructed as a pseudo-random binary sequence (PRBS) using the same generator as the frame scrambler (Figure 2) except with its initial seed equal to the value of the TXFN field in the frame header (Table 10). If the value of TXFN used to seed the PRBS is equal to the state of the frame scrambler, the seed shall be over-written with a TBD-1 value for its seed.

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

3.4.4.2. MGMT Frames

The MGMT frame type is provided for management frames. These frames are used for inter-OCT communications.

3.4.4.2.1. Header Construction

Modem MGMT frames are signaled in the frame header by field FRAME_TYPE=10 (Table 10).

3.4.4.2.2. Payload Construction

Modem MGMT frames are 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 is the same as for data frames.

3.4.5. Ethernet Encapsulation

3.4.5.1. Overview of Ethernet Packet Encapsulation

Requirement OCT-034: The OCT data plane shall encapsulate Ethernet packets as Free Space Optical (FSO) frames for transport across the optical link as described herein.

The processing steps are illustrated functionally in Figure 5.

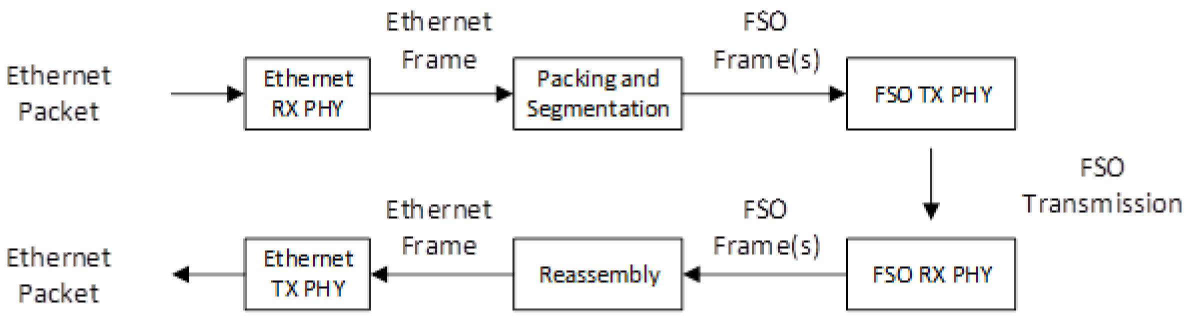

Figure 5: Ethernet Encapsulation

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

3.4.5.1.1. 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 must be queued to the Packing and Segmentation block for encapsulation as FSO frames.

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

3.4.5.1.2. Packing and Segmentation

The *Packing and Segmentation* operation (Figure 5) must 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 must preserve the ingress order of Ethernet packets.

3.4.5.1.3. 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 6. The bytes must be written into the payload FEC frame in physical byte order. The bytes must be consecutive, per word in Figure 6, 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 must count up naturally for each 32-bit word in Figure 6.

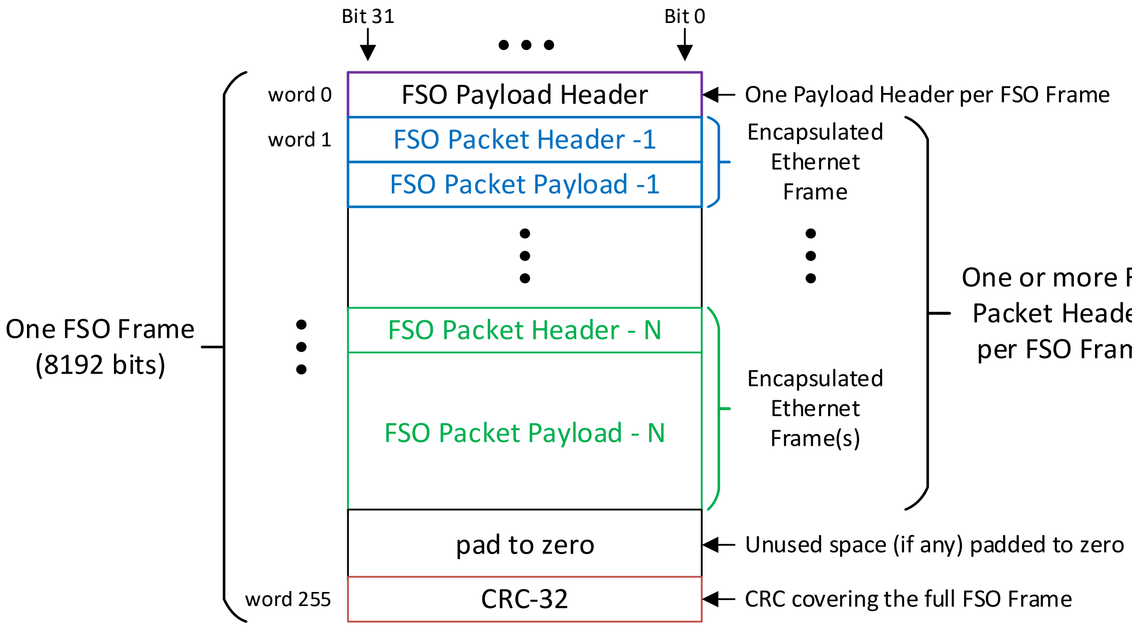

Figure 6: FSO Payload Frame Format

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

There must not be any zero-pad space except at the end of the FSO frame as illustrated in Figure 6.

Note that the CRC-32 described in Figure 6 is the same CRC-32 previously described in and is repeated here for clarity.

3.4.5.1.4. FSO Payload and Packet Headers

Requirement OCT-035: Every FSO frame shall start with an FSO Payload Header.

Requirement OCT-036: There shall be exactly one FSO Payload Header (32 bits) per FSO frame.

Requirement OCT-037: The contents of the FSO frame and packet headers shall follow the definition presented in Table 13.

Table 13: 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 is 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 13 is unrelated to the modem's ARQ signaling in Table 10.

The system must 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 13) 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 packet header regardless of whether the Ethernet frame is segmented into the following FSO frame.

3.4.5.1.5. Ethernet Byte Ordering, Padding, and CRC

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

Ethernet frame payload bytes shall be written into the FSO frame (Figure 6) 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 14. The Payload Header (Table 13) 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 14: Ethernet Frame Byte Ordering into FSO Logical Frame

FSO word number	contents	**31-24**	**23-16**	**15-8**	**7-0**
word 0	Payload Header	AB[31:24], seq_num[23:14], length[13:0]			
word 1	Packet Header	CDEF[31:18], reserved [17:16], length[13:0]			
word 2	Ethernet bytes	ETH_Byte_3	ETH_Byte_2	ETH_Byte_1	ETH_Byte_0
		…			
word M		Zero_Pad	Zero_Pad	ETH_Byte_n-1	ETH_Byte_n-2

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 3.4.5.1.4).

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

3.4.5.1.6. 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 5) 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 13) is incorrect shall be discarded entirely.
- Any FSO Packet Header within any FSO frame (Table 13) whose magic number is incorrect shall be discarded.
- Any FSO Packet Header whose length field is inconsistent shall be discarded.

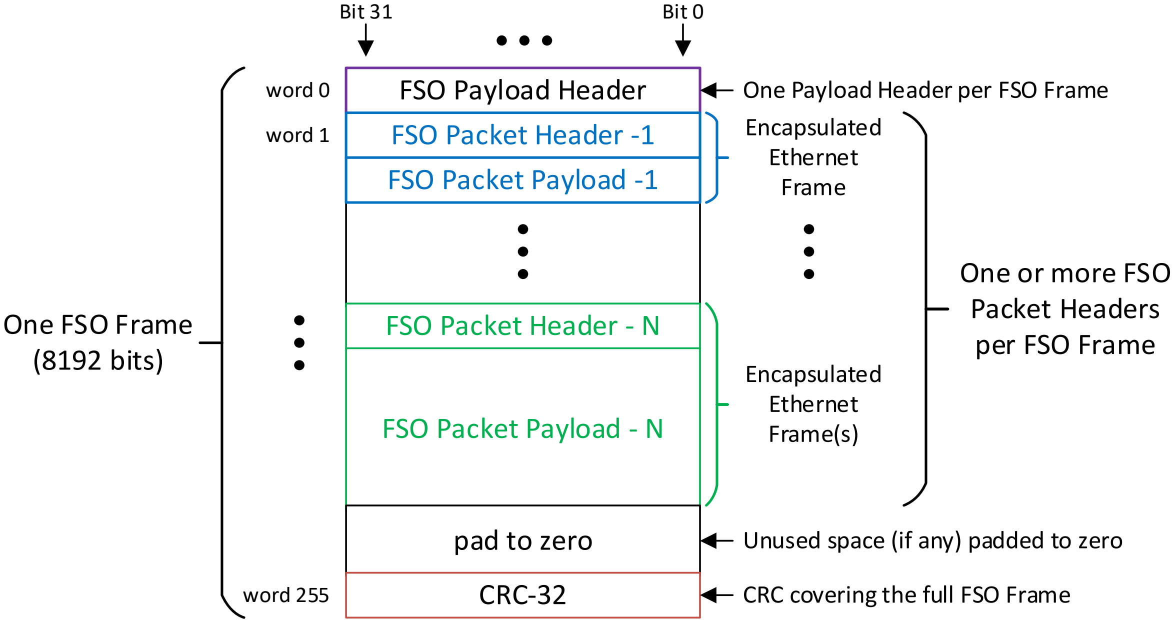

Figure 7: FSO Payload Frame Format

3.4.6. Effective Data Rate

The effective data rates for the primary OCT modem frame configurations are summarized in Table 15. For brevity, the data rates are tabulated only for the extreme settings of payload FEC (R=8/9 and R=1/2) with the LDPC codec.

Table 15: Effective Data Rates for Frame Configurations

Baud rate (Msps)	Line Code	Baud Time (ns)	Frame Duration (µsec)		Payload Data Rate (Mbps)		FCCH Data Rate (Mbps)	
			R=8/9	R=1/2	R=8/9	R=1/2	R=8/9	R=1/2
2500	None	0.4	4.09	6.96	1994.52	1172.68	11.73	6.90
1250	Manchester	0.8	8.18	13.92	997.26	586.34	5.87	3.45
625		1.6	16.36	27.83	498.63	293.17	2.93	1.72
312.5		3.2	32.73	55.67	249.32	146.59	1.47	0.86
156.25		6.4	65.46	111.33	124.66	73.29	0.73	0.43
78.125		12.8	130.92	222.67	62.33	36.65	0.37	0.22

The quoted data rates account for all sources of overhead including preamble, header, CRC’s, and FEC.

3.5. Circulant Tables for Payload LDPC Code

The payload FEC features a low-density parity check (LDPC) code with performance near the Shannon capacity limit in additive white Gaussian noise. The key attributes of the payload LDPC code are summarized in Table 16.

Table 16: LDPC Code Properties

LDPC Code	Family	Quasi-cyclic
	Parity Check Matrix (PCM)	Single-weight circulant
		Circulant size 64
		Irregular structure
	Block size	8192 information bits
	Rate	R=1/2 (lowest), number of non-zero circulants = 1408
		R=8/9 (highest), number of non-zero circulants = 512
Encoder	Algorithm	Pre-computed generator matrix (G)
		G is dense but has a quasi-cyclic structure on each of its $S \times S$ tiles ($S = 64$)
Decoder	Algorithm	Normalized min-sum algorithm
		Up to 10 iterations, early-exit feature when syndrome is satisfied

3.5.1. LDPC Code Tables

The payload LDPC code is quasi-cyclic with a single-weight circulant size of $S = 64$. Per the specifications in Table 16, the code's parity check matrix has these properties:

- Number of information bits: 8192
- Maximum number of parity bits: 8192
- Circulant size: 64

The payload FEC code has a single-weight circulant structure and can compactly be represented by a table of its circulants, requiring a matrix with

$$\left(\frac{8192}{64}\right) rows \times \left(\frac{16384}{64}\right) columns$$

with each entry indicating either the circulant's shift value or negative 1 for no connection.

The complete table of circulants describing the payload LDPC code is in Table 17.

Table 17: LDPC Code Circulants

Row	# of Circulants	Circulant values: shift(offset)
1	32	61(3), 16(5), 22(9), 43(15), 18(20), 59(24), 48(27), 44(31), 22(33), 39(40), 25(42), 1(45), 45(52), 41(56), 32(57), 23(62), 2(65), 54(71), 31(75), 53(79), 47(84), 19(85), 18(96), 55(104), 37(105), 0(112), 5(118), 18(124), 16(128), 18(129), 61(136), 43(139)
2	32	45(2), 20(8), 45(12), 27(14), 46(19), 50(23), 11(26), 52(30), 50(36), 27(39), 6(41), 12(48), 18(51), 7(55), 31(60), 30(61), 0(68), 48(70), 27(74), 32(78), 25(83), 17(88), 13(95), 23(103), 23(108), 2(111), 41(117), 53(123), 52(127), 31(132), 42(135), 15(138)
3	32	30(1), 3(7), 3(11), 58(13), 34(18), 36(22), 60(25), 3(29), 44(35), 38(38), 9(44), 17(47), 1(50), 34(54), 58(59), 27(64), 40(67), 28(69), 7(73), 38(77), 48(82), 3(87), 37(94), 15(102), 10(107), 61(110), 27(120), 1(122), 16(126), 44(131), 48(134), 5(137)
4	32	16(4), 38(6), 22(10), 37(16), 4(17), 52(21), 17(28), 46(32), 7(34), 16(37), 39(43), 47(46), 9(49), 11(53), 48(58), 33(63), 3(66), 28(72), 4(76), 43(80), 19(81), 44(86), 4(93), 0(101), 39(106), 10(109), 57(119), 44(121), 13(125), 58(130), 51(133), 62(140)
5	32	19(1), 34(8), 44(12), 51(13), 5(18), 58(24), 34(25), 26(31), 10(36), 2(40), 14(44), 60(47), 51(50), 30(53), 61(57), 46(64), 44(66), 32(69), 57(74), 60(79), 36(83), 23(85), 54(89), 38(100), 46(105), 15(111), 59(114), 12(121), 37(125), 48(135), 58(139), 33(143)
6	32	42(3), 20(6), 26(10), 8(15), 56(20), 47(22), 56(27), 2(29), 29(34), 52(38), 40(42), 48(45), 41(52), 17(55), 62(59), 42(62), 43(68), 13(71), 46(76), 32(77), 9(81), 45(87), 59(91), 10(98), 31(107), 49(109), 10(116), 47(123), 39(127), 16(133), 14(137), 39(141)
7	32	18(2), 62(5), 30(9), 43(14), 43(19), 8(21), 9(26), 40(32), 24(33), 2(37), 32(41), 19(48), 45(51), 11(54), 31(58), 47(61), 61(67), 6(70), 30(75), 48(80), 32(84), 17(86), 11(90), 16(97),

		30(106), 55(112), 44(115), 17(122), 36(126), 12(136), 42(140), 33(144)
8	32	59(4), 62(7), 63(10), 40(13), 48(20), 8(22), 0(28), 39(30), 30(36), 34(39), 10(43), 29(47), 50(52), 61(56), 14(59), 63(63), 47(68), 36(71), 63(73), 60(78), 11(85), 12(92), 22(96), 45(99), 33(101), 29(111), 4(114), 19(119), 33(125), 63(132), 27(138), 41(141)
9	32	28(1), 42(8), 9(11), 24(14), 9(17), 36(23), 14(25), 14(31), 19(33), 31(40), 40(44), 26(48), 15(49), 9(53), 46(60), 24(64), 54(65), 38(72), 12(74), 14(79), 7(86), 30(89), 47(93), 63(100), 6(102), 30(112), 37(115), 42(120), 1(126), 1(129), 50(139), 9(142)
10	32	47(3), 62(6), 41(9), 30(16), 52(19), 7(21), 31(27), 13(29), 7(35), 33(38), 28(42), 30(46), 22(51), 24(55), 39(58), 44(62), 20(67), 44(70), 39(76), 15(77), 46(88), 7(91), 38(95), 13(98), 57(104), 46(110), 3(113), 28(118), 40(128), 45(131), 44(137), 6(144)
11	32	63(2), 49(5), 50(12), 48(15), 24(18), 30(24), 53(26), 5(32), 41(34), 29(37), 51(41), 7(45), 11(50), 43(54), 50(57), 4(61), 53(66), 39(69), 40(75), 38(80), 49(87), 18(90), 2(94), 53(97), 34(103), 11(109), 18(116), 16(117), 38(127), 38(130), 24(140), 41(143)
12	32	61(4), 57(7), 17(11), 53(16), 43(17), 9(23), 9(28), 43(30), 62(35), 11(39), 16(43), 48(46), 46(49), 35(56), 49(60), 50(63), 4(65), 21(72), 20(73), 3(78), 42(82), 60(88), 9(92), 25(99), 44(108), 2(110), 57(113), 19(124), 26(128), 43(134), 13(138), 33(142)
13	32	26(1), 14(8), 47(9), 36(14), 3(20), 13(23), 4(27), 61(29), 46(36), 61(38), 20(44), 55(48), 5(51), 5(53), 39(59), 13(64), 37(68), 57(71), 29(76), 10(80), 48(83), 20(91), 48(95), 44(97), 16(102), 3(107), 15(114), 42(117), 45(121), 49(132), 31(133), 3(144)
14	32	38(3), 15(6), 42(11), 17(16), 14(18), 15(21), 2(25), 5(31), 42(34), 62(40), 22(42), 2(46), 41(49), 51(55), 30(57), 40(62), 48(66), 38(69), 30(74), 13(78), 56(81), 44(89), 0(93), 54(99), 31(104), 53(105), 50(116), 9(119), 9(123), 57(130), 30(135), 53(142)
15	32	30(4), 52(7), 4(12), 21(13), 39(19), 60(22), 37(26), 8(32), 24(35), 44(37), 9(43), 51(47), 15(50), 38(56), 44(58), 8(63), 51(67), 46(70), 25(75), 41(79), 6(82), 63(90), 27(94),

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

33	9	60(10), 5(16), 61(25), 36(43), 38(61), 13(66), 17(108), 62(123), 37(161)
34	9	36(11), 5(13), 20(26), 49(44), 60(62), 44(67), 8(105), 6(124), 31(162)
35	9	40(12), 30(14), 9(27), 34(41), 27(63), 18(68), 37(106), 34(121), 2(163)
36	9	52(9), 7(15), 55(28), 30(42), 43(64), 61(65), 52(107), 11(122), 20(164)
37	9	29(2), 29(14), 34(31), 27(45), 1(51), 16(70), 41(111), 50(128), 17(165)
38	9	46(3), 26(15), 11(32), 58(46), 4(52), 28(71), 54(112), 55(125), 24(166)
39	9	29(4), 45(16), 62(29), 5(47), 58(49), 50(72), 6(109), 30(126), 23(167)
40	9	51(1), 34(13), 15(30), 42(48), 38(50), 54(69), 44(110), 6(127), 2(168)
41	9	32(4), 45(8), 52(20), 26(36), 15(54), 18(73), 59(98), 2(115), 13(172)
42	9	4(1), 18(5), 13(17), 8(33), 45(55), 23(74), 44(99), 23(116), 26(169)
43	9	34(3), 38(7), 1(19), 47(35), 27(53), 24(76), 34(97), 25(114), 49(171)
44	9	56(2), 17(6), 62(18), 16(34), 59(56), 20(75), 26(100), 26(113), 21(170)
45	9	19(8), 14(12), 42(21), 6(39), 60(59), 5(77), 56(101), 28(120), 26(173)
46	9	25(5), 24(9), 52(22), 6(40), 1(60), 5(78), 33(102), 15(117), 0(174)
47	9	55(6), 48(10), 33(23), 7(37), 16(57), 20(79), 11(103), 12(118), 44(175)
48	9	46(7), 12(11), 17(24), 40(38), 20(58), 59(80), 48(104), 0(119), 20(176)
49	8	49(2), 38(15), 40(22), 5(33), 4(59), 42(74), 42(127), 8(177)
50	8	31(3), 20(16), 10(23), 26(34), 12(60), 9(75), 44(128), 38(178)
51	8	55(4), 24(13), 22(24), 53(35), 19(57), 28(76), 3(125), 59(179)
52	8	53(1), 6(14), 23(21), 56(36), 59(58), 5(73), 7(126), 49(180)
53	8	12(4), 22(5), 32(26), 37(37), 2(64), 28(80), 28(113), 9(181)
54	8	0(1), 48(6), 33(27), 21(38), 12(61), 37(77), 1(114), 7(182)
55	8	4(2), 40(7), 58(28), 5(39), 1(62), 28(78), 9(115), 52(183)

56	8	14(3), 7(8), 20(25), 51(40), 15(63), 18(79), 62(116), 41(184)
57	8	40(5), 60(11), 16(32), 33(41), 14(49), 19(66), 1(118), 40(185)
58	8	40(6), 29(12), 41(29), 12(42), 44(50), 57(67), 23(119), 39(186)
59	8	6(7), 8(9), 41(30), 49(43), 40(51), 2(68), 57(120), 48(187)
60	8	39(8), 46(10), 36(31), 42(44), 56(52), 37(65), 38(117), 10(188)
61	8	56(12), 44(13), 19(18), 13(46), 5(56), 33(69), 4(124), 16(189)
62	8	29(9), 63(14), 35(19), 55(47), 34(53), 57(70), 19(121), 44(190)
63	8	28(10), 16(15), 34(20), 34(48), 8(54), 25(71), 40(122), 47(191)
64	8	24(11), 6(16), 14(17), 21(45), 23(55), 1(72), 11(123), 39(192)
65	8	23(8), 53(15), 42(20), 54(37), 53(61), 32(73), 31(126), 5(193)
66	8	8(5), 46(16), 18(17), 15(38), 17(62), 56(74), 5(127), 59(194)
67	8	6(6), 62(13), 23(18), 60(39), 36(63), 22(75), 32(128), 28(195)
68	8	34(7), 13(14), 0(19), 38(40), 40(64), 15(76), 47(125), 17(196)
69	8	44(1), 37(11), 41(21), 35(43), 59(50), 34(79), 16(114), 7(197)
70	8	60(2), 58(12), 15(22), 31(44), 6(51), 22(80), 29(115), 46(198)
71	8	39(3), 19(9), 44(23), 50(41), 19(52), 52(77), 34(116), 9(199)
72	8	35(4), 29(10), 62(24), 61(42), 36(49), 43(78), 59(113), 3(200)
73	8	0(7), 57(14), 63(26), 26(47), 47(54), 36(66), 49(120), 59(201)
74	8	55(8), 24(15), 30(27), 30(48), 16(55), 28(67), 13(117), 43(202)
75	8	39(5), 33(16), 49(28), 19(45), 7(56), 23(68), 26(118), 3(203)
76	8	45(6), 32(13), 9(25), 19(46), 8(53), 28(65), 58(119), 25(204)
77	8	37(4), 11(11), 10(32), 56(33), 52(59), 9(69), 28(121), 25(205)
78	8	3(1), 27(12), 59(29), 46(34), 0(60), 49(70), 2(122), 24(206)
79	8	54(2), 37(9), 10(30), 60(35), 35(57), 21(71), 42(123), 38(207)
80	8	30(3), 3(10), 1(31), 55(36), 3(58), 13(72), 17(124), 54(208)
81	8	59(1), 31(7), 46(28), 59(35), 53(64), 42(76), 54(122), 2(212)
82	8	31(2), 12(8), 8(25), 5(36), 57(61), 24(73), 34(123), 12(209)
83	8	3(4), 28(6), 22(27), 6(34), 9(63), 56(75), 1(121), 43(211)
84	8	12(3), 50(5), 29(26), 3(33), 46(62), 51(74), 34(124), 57(210)
85	8	25(7), 18(9), 34(32), 51(38), 52(51), 11(79), 12(126), 56(213)
86	8	52(8), 8(10), 1(29), 63(39), 8(52), 42(80), 35(127), 27(214)
87	8	31(5), 5(11), 25(30), 7(40), 24(49), 30(77), 1(128), 27(215)
88	8	1(6), 1(12), 21(31), 48(37), 24(50), 36(78), 29(125), 12(216)
89	8	15(12), 22(16), 29(20), 10(44), 10(54), 41(66), 5(116), 0(217)

90	8	61(9), 38(13), 35(17), 60(41), 20(55), 38(67), 25(113), 38(218)
91	8	58(10), 58(14), 2(18), 50(42), 19(56), 61(68), 2(114), 32(219)
92	8	31(11), 4(15), 62(19), 26(43), 50(53), 38(65), 51(115), 61(220)
93	8	49(4), 23(13), 35(22), 41(48), 12(58), 17(72), 50(119), 14(221)
94	8	48(1), 21(14), 14(23), 63(45), 28(59), 13(69), 5(120), 32(222)
95	8	20(2), 41(15), 52(24), 8(46), 29(60), 53(70), 29(117), 4(223)
96	8	37(3), 35(16), 48(21), 52(47), 60(57), 6(71), 38(118), 40(224)
97	7	25(6), 26(12), 39(18), 60(63), 56(66), 33(104), 8(228)
98	7	59(7), 33(9), 41(19), 29(64), 26(67), 14(101), 3(225)
99	7	47(5), 33(11), 47(17), 63(62), 44(65), 55(103), 5(227)
100	7	63(8), 47(10), 7(20), 1(61), 3(68), 2(102), 23(226)
101	7	34(12), 17(15), 63(23), 7(50), 60(72), 34(107), 11(229)
102	7	5(9), 44(16), 4(24), 21(51), 3(69), 39(108), 37(230)
103	7	50(10), 4(13), 58(21), 5(52), 27(70), 23(105), 61(231)
104	7	45(11), 38(14), 37(22), 43(49), 26(71), 43(106), 25(232)
105	7	38(1), 29(15), 43(26), 1(53), 14(74), 43(109), 17(234)
106	7	42(4), 28(14), 31(25), 21(56), 12(73), 53(112), 61(233)
107	7	33(2), 63(16), 42(27), 59(54), 1(75), 1(110), 11(235)
108	7	63(3), 49(13), 22(28), 47(55), 20(76), 4(111), 45(236)
109	7	24(1), 31(8), 25(32), 58(58), 50(79), 17(98), 11(237)
110	7	46(2), 57(5), 24(29), 6(59), 49(80), 26(99), 19(238)
111	7	20(3), 2(6), 50(30), 62(60), 41(77), 29(100), 41(239)
112	7	26(4), 2(7), 9(31), 33(57), 26(78), 26(97), 62(240)
113	6	26(5), 35(13), 41(60), 23(79), 49(88), 47(241)
114	6	57(6), 31(14), 45(57), 16(80), 16(85), 33(242)
115	6	42(7), 52(15), 25(58), 63(77), 49(86), 2(243)
116	6	24(8), 58(16), 8(59), 49(78), 16(87), 63(244)
117	6	1(4), 0(9), 29(61), 16(66), 44(91), 33(245)
118	6	61(1), 40(10), 41(62), 59(67), 43(92), 61(246)
119	6	12(2), 25(11), 21(63), 35(68), 17(89), 32(247)
120	6	49(3), 54(12), 26(64), 31(65), 12(90), 53(248)
121	6	4(7), 27(15), 36(51), 59(72), 29(95), 25(249)
122	6	57(8), 21(16), 27(52), 57(69), 14(96), 24(250)
123	6	52(5), 29(13), 38(49), 22(70), 37(93), 40(251)
124	6	0(6), 42(14), 36(50), 51(71), 58(94), 30(252)
125	6	58(4), 43(9), 19(55), 9(74), 1(81), 55(253)

126	6	39(1), 31(10), 50(56), 3(75), 5(82), 6(254)
127	6	13(2), 28(11), 25(53), 41(76), 35(83), 26(255)
128	6	18(3), 36(12), 9(54), 29(73), 59(84), 19(256)

3.5.2. LDPC Code Rates

The OCT modem implementation supports the four payload FEC code rates listed in Table 18. The table should be read, for a given code rate, as the first N bit of the parity check matrix appended to the 8192 data bits to form the designated code rate.

Table 18: Payload FEC Code Rates

Code Rate	Data bits	Parity Bits
8/9	8192	1024
4/5		2048
2/3		4096
1/2		8192

The payload FEC code rate is set prior to acquisition and does not change once established.

4. 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 document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below.

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5. Appendix A: Spiral Scan Definition

Scans may either be continuous or stepped. Continuous scans will move with constant-velocity and follow an Archimedean Spiral or an approximation thereof. These are referred to as constant velocity Archimedean Spiral (CVAS) scans.

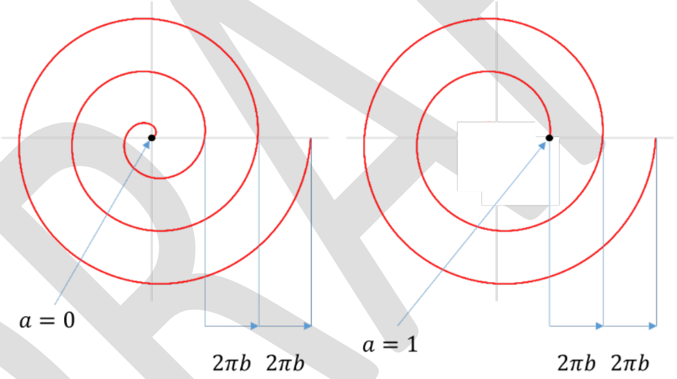
Archimedean Spiral Scans are defined in polar coordinates by

$$r = a + b \cdot \theta$$

Equation 5-1

Where a defines the initial distance from the center point of the spiral from the origin and b controls the distance between loops. The scan step size is the distance between the spirals along the line extending from the origin in the direction of θ and is equal to $\frac{b}{2\pi}$.

Figure 8. Two examples of Archimedean Spirals for a=0 and a=1. For integer values of a, the spiral will be in the original "rotation." For non-integer values of a, the spiral is rotated such that $r(\theta) = a$.



The distance travelled (arc length) between two points on the curve, defined by θ_1 and θ_2, is

$$s(\theta_1, \theta_2) = \frac{b}{2}\left[\theta\sqrt{1+\theta^2} + \ln\left(\theta + \sqrt{1+\theta^2}\right)\right]_{\theta_1}^{\theta_2}$$

Equation 5-2

Taking $\theta_1 = 0 \; and \; \theta_2 = theta$ the scan time, t_{scan}, is

$$t_{scan} = \frac{d_{scan}}{v_{scan,0}} = \frac{b}{2 \cdot v_{scan,0}}\left[\theta\sqrt{1+\theta^2} + \ln\left(\theta + \sqrt{1+\theta^2}\right)\right]$$

Equation 5-3

Where $v_{scan,0}$ is the constant scan rate.

The distance between consecutive "loops" of the spiral must permit both the transmit beam and receiver sensor to fully scan the search cone. The receiver sensor FOV (η_{RX}) and transmitter's cone of divergence (η_{TX}) define the scan parameters. The lesser of η_{TX} and η_{RX} defines the scan step size

$$\eta_{scan} = \min\{\eta_{TX}, \eta_{RX}\}$$

Equation 5-4

The transmitter's cone of divergence is defined by the divergence angle of the portion of the transmitted beam that is above the detection threshold of the remote receiver at the expected range. This may be set at the beam's FWHM, $\frac{1}{e}$, $\frac{1}{e^2}$, or another point as required to accommodate the beam's parameters. To overlap consecutive loops of the scan, the overlap angle, $\eta_{overlap}$, may be subtracted from the transmit or receive angle, resulting in:

$$\eta_{scan} = \min\{\eta_{TX}, \eta_{RX}\} - \eta_{overlap}$$

Equation 5-5

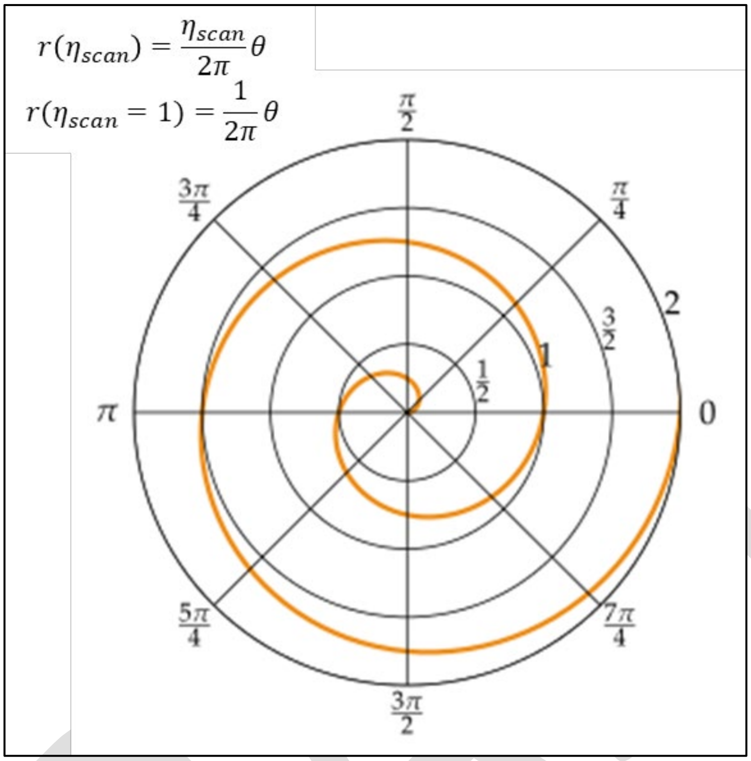
Where α_{scan} is the angular scan step size, b in Equation 5-1 multiplied by 2π. Setting $a = 0$ in Equation 5-1 so that scans begin at the origin, we now have

$$r = \frac{1}{2\pi}\eta_{scan} \cdot \theta$$

Equation 5-6

This is illustrated in Figure 9. Archimedean Spiral for $\eta_{scan} = 1$.

Figure 9. Archimedean Spiral for $\eta_{scan} = 1$.



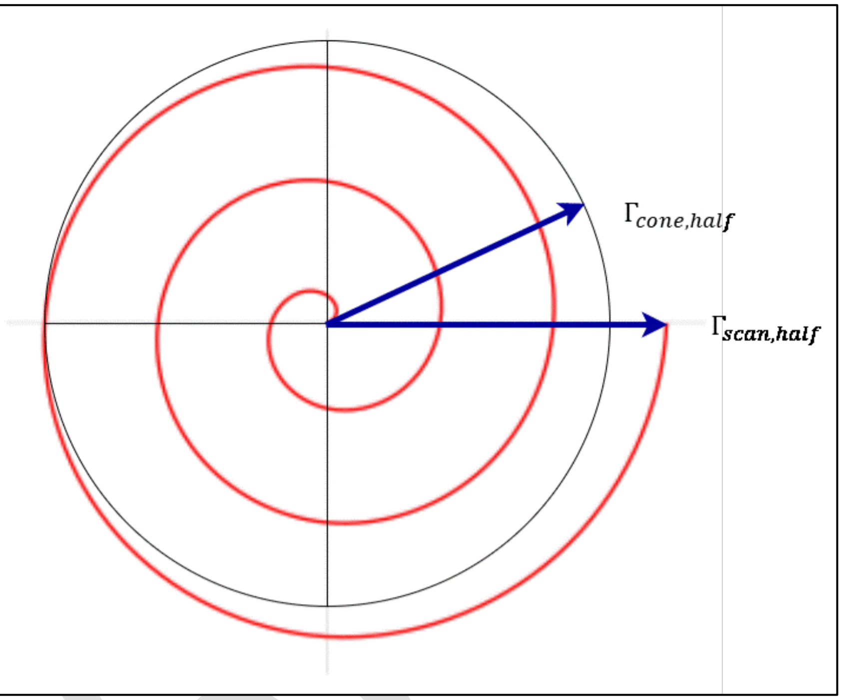
For a CVAS scan, the duration in time of the scan is

$$t_{scan} = \frac{d_{scan}}{v_{scan,0}} = \frac{\eta_{scan}}{4\pi v_{scan,0}}\left[\theta\sqrt{1+\theta^2} + \ln\left(\theta + \sqrt{1+\theta^2}\right)\right] \qquad \text{Equation 5-7}$$

The total angular scan area is defined by the cone half-angle, Γ_{cone}. In order to completely scan the cone angle with the circular divergent beam or sensor FOV, the scan must end at $r = \Gamma_{scan} = \Gamma_{cone} + \frac{\eta_{scan}}{2}$. The half-angle of the scan, $\Gamma_{scan,half}$ is also used in the equations below.

Figure 10. The three-period Archimedean spiral covering a search area defined by Γ_{cone}. Note that the scan must extend beyond the circle in order to ensure that the cone defined by Γ_{cone} is

fully-inscribed within the scan region. The scan cone angle is Γ_{scan} (please note that the half angle is annotated in the figure).



Notes:
- Black circle: boundary of the area to be scanned
- Red Line: the scan trajectory
  - The basic equation for the trajectory is $r = a + b \cdot \theta$
  - r is the radius from the origin
  - θ is the angle from the x-axis in the figure
  - Origin: is the pointing vector between the local and remote systems
- The axes represent the angles (ρ and ϕ) from the initial pointing vector

The scan of this cone is completed when $\theta = \theta_2$ and . This condition is met when

$$\Gamma_{scan,half} = r(\theta_2) = \theta_2 * b = \theta_2 \cdot \frac{\eta_{scan}}{2\pi}$$ Equation 5-8

θ_2 then becomes

$$\theta_2 = \frac{2\pi\Gamma_{\mathrm{scan,half}}}{\eta_{scan}}$$ Equation 5-9

Which then, for the full cone angle Γ_{scan},

$$\theta_2 = \frac{\pi\Gamma_{scan}}{\eta_{scan}}$$ Equation 5-10

Inserting Equation 5-10 into Equation 5-7 gives

$$t_{scan}(\Gamma) = \frac{d_{scan}(\Gamma)}{v_{scan,0}} = \frac{\eta_{scan}}{4\pi v_{scan,0}}\left[\frac{\pi\Gamma}{\eta_{scan}}\sqrt{1+\left(\frac{\pi\Gamma}{\eta_{scan}}\right)^2} + \ln\left(\frac{\pi\Gamma}{\eta_{scan}} + \sqrt{1+\left(\frac{\pi\Gamma}{\eta_{scan}}\right)^2}\right)\right]$$

Equation 5-11

The scan may now be defined by the parameters in the following table:

Table 19

Parameter	Description	Notes
$\boldsymbol{\Gamma_{scan}}$	The cone angle of the scan.	This is defined for a circular cone.
$\boldsymbol{t_{scan}}$	The scan duration in time.	The scan duration is the time required to complete one spiral scan of the cone.
$\boldsymbol{\eta_{scan}}$	The required scan step-size.	The scan step size is the distance between the spirals along the line extending from the origin in the direction of θ.

5.1. Spiral Scan

In a Spiral Scan process, both OCTs execute constant-velocity Archimedean Spiral (CVAS) scans simultaneously.

5.2. Nested Spiral Scan

For a nested spiral scan, one additional parameter is required: the step size for the outer loop of the nested scans. The OCT assigned to the outer loop will step and stare along the defined Archimedean Spiral while the OCT assigned to the inner loop performs a CVAS scan. The step size, denoted η_{step}, is the distance along the spiral scan path to be taken between steps. This slew and settle must complete within the time t_{step}.

The total scan duration t_{scan} is then

$$t_{scan} = \sum_{n} \left[t_{scan}^{(inner\ loop)} + t_{step} \right]$$

Equation 5-12

Where $t_{scan,inner\ loop}$ is the total time to complete a single CVAS scan.