Optical Communications Terminal (OCT) Standard Version 3.0

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1 Introduction

This document provides the interoperability specifications 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) free-space optical communications (FSOC).

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 (T0). T0 added sufficient detail to the initial OISL Standard that multi-vendor interoperability could be demonstrated. Since early 2020, significant advancements have been made across the Optical Communications Terminal (OCT) market. These advancements have prompted the modification of the OISL Standard and those modifications are captured in this document.

The OISL Standard has been renamed the Optical Communications Terminal (OCT) Standard due to its applicability to S2G, S2M, and S2A links in addition to S2S links. Combined, S2G, S2M, and S2A links are referred to as space-to-terrestrial (S2T) FSOC links.

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 Compliance with the OCT Standard

1.1.1 Interoperability of OCT Standard Systems

Systems that are required to comply with this OCT Standard have, first and foremost, the requirement to be interoperable with other OCT Standard FSOC systems.

Requirement OCT-001: OCT Standard-compliant systems shall be interoperable with other OCT Standard-compliant systems.

1.1.2 Errata, Bug Reports, Clarifications, and Modification Requests

Requirement OCT-002: Notes, bug reports, requests for clarification, errata, and requests for modifications to this OCT Standard shall be submitted to:

Space Development Agency / Transport Cell / Optical Communications

Contact information may be found on the cover page of this document.

1.1.3 Version Control

Requirement OCT-003: OCT Standard-compliant systems shall document the list of OCT Standard versions with which they are compliant.

Requirement OCT-004: OCT Standard Compliance shall be reported as “Compliant with SDA OCT Standard <Version>”. The version number shall be expressed in the following format:

<Version> = <Major Release Number>.<Minor Release Number>.<Patch Number>

The components of the version number are defined as follows:

- Patch Number
    - Patches correct errata, address bug reports, and provide clarifications or corrections.
- Minor Release Number
    - Minor Releases add functionality, protocols, or provide significant modifications while enabling existing components to remain compatible within a Major Version
- Major Release Number
    - Major Releases change significant functionality. OCT Systems compliant with a Major Release are compatible with one another but are not guaranteed to be compatible with OCT Standard Compliant Systems from a different Major Release.

1.2 Elements of the OCT Standard

This document provides descriptions of two Open System Interconnection (OSI) Model layers:

- OSI Layer 1: Physical Layer
- OSI Layer 2: Synchronization and Channel Coding Layers (the "lower" portion of OSI Layer 2 as defined by CCSDS in [3])

This document's scope includes the OCT to OCT (O2) interface. Requirements on external systems (e.g. derived requirements such as pointing stability, power, network interfaces, etc.) are be driven by requirements within this OCT Standard.

The term *OCT Standard Complaint* denotes an OCT System that fully implements the O2 interface **and** those requirements (directly stated, derived, implied, or otherwise) on the external systems. OCT Standard Compliant OCT Systems are interoperable with other systems within the same Major Version.

This OCT Standard explicitly **does not specify** the following:

- Interfaces to the spacecraft bus
- Telemetry, Tracking and Control (TT&C) System
- Network interface(s)

Note: the above list of items not specified by the OCT Standard is not exclusive.

1.2.1 Overview of Layer 1: Physical Layer

The Physical Layer (Layer 1) is the lowest layer in the OSI model. For the case of the OCT, the Physical Layer must define both the communications and spatial acquisition channels (referred to as pointing, acquisition, and tracking (PAT)). Section 2 defines the Physical Layer through definition of the laser parameters (e.g. wavelength, channel spacing, and spectral width) and the modulation parameters (e.g. On-Off Keying Non Return-to-Zero (OOK-NRZ)). 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.

1.2.1.1 Overview of PAT

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.

Spatial acquisition is accomplished through the PAT process, which must be coordinated temporally.

Requirement OCT-005: OCT Standard Compliant systems shall not assume access to real-time side-channels for communications and coordination of the PAT process.

This acquisition process must be synchronous. Real-time O2 communications do not occur prior to stand-up of the communications channel. This requires that the acquisition processes on the pair of terminals be both well-choreographed and synchronized to a common clock.

Requirement OCT-006: OCTs shall have a real-time clock synchronized to absolute time (the *OCT Clock*).

> **Note on Requirement OCT-006:** the OCT Clock's accuracy, stability, method of synchronization, and other pertinent clock requirements shall be derived for the specific OCT System implementation.

This choreography is governed by the state machine and its associated parameters.

Requirement OCT-007: OCTs shall provide the capability to reference real-time events (e.g. timers, delays, triggers, events, etc.) to the OCT Clock.

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 may be accomplished through a closed-loop tracking system which uses the remote signal as the measurement reference. Corrections are typically fed to a course-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.

> **Note:** This notional course and fine tracking architecture is one potential option and shall not be assumed as a requirement for compliance with the OCT Standard.

1.2.2 Overview of Layer 2: Synchronization and Coding

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 error-corrected transmission (e.g. Forward Error Correction (FEC), scrambling, and line codes) as well as the structure of the data (e.g. framing).

1.3 Requirements

Requirements in this document take two forms:

1. Normative text indicating **'shall' or 'must'** which **indicate a binding and verifiable specification**

2. Enumerated Requirements, which will typically include normative text. These are specifically labeled for reference.

Requirement OCT-008: OCT Standard Compliant Systems shall implement all normative and enumerated requirements in this document.

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

Requirement OCT-<NNN>: <Requirement Description>

Requirements for the OCT System that are not specified in this OCT Standard shall be derived for the specific implementation. This shall include those requirements levied on and by the host (e.g. the spacecraft bus).

Requirement OCT-009: OCT Standard Compliant Systems shall implement derived requirements as needed to enable successful operations and to ensure interoperability.

> **Note on Requirement OCT-009:** Space vehicle and OCT system vendors shall determine derived requirements through their individual systems engineering and design processes.

1.4 Definitions

Term	Definition
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.
Baud Rate	The number of symbols per second.
Baud Time	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).
Bit Numbering Convention	The convention used to identify each bit in an N-bit field will conform to Section 1.7 in (1).
Bitrate	The number of bits conveyed per unit of time. Default unit of time: seconds.
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]
Coded Bit-Error Rate	The number of bit errors per unit time prior to applying Forward Error Correction.
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.
Decoded Bit-Error Rate	The number of bit errors per unit time prior to applying Forward Error Correction.
Extinction Ratio	Extinction ratio is the ratio of two optical power levels.
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 angular area of a sensor. The solid angle may be expressed in steradians or, equivalently, as a cone angle. FOVs for rectalinear sensors may be represented the rectangular cone angles. Circular cone angles may represent circular sensors, inscribed or circumscribed rectilinear sensors, circularly-symmetric optical sytems, etc. Descriptions must be specified for specific FOVs in order to communicate the solid angle and geometry being represented. See also HFOV and FFOV.
Frame Error Rate	The ratio of number of frames received in error to total number of transmitted frames.
Full Field of View	The expression for FOV specified by the diameter (angular or spatial) of the FOV or the half-angle for a general cone.
Half Field of View (HFOV)	The expression for FOV specified by the radius (angular or spatial) of the FOV for a circular cone or the half-angle for a general cone.
Irradiance	Irradiance is the radiant flux through a surface per unit area. The SI unit for irradiance is the watt per square meter (W/m^2).
Line Code	A pattern of voltage, current, or photons used to represent digital data transmitted down a transmission line. [4]
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]
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]
Modulation Index (MI)	Modulation index is the ratio of the modulation excursions of a signal to the level of the unmodulated carrier.
Packet Error Rate	The ratio of number of Ethernet packets received in error to total number of transmitted Ethernet packets.
Polarization Extinction Ratio (PER)	The extinction ratio for orthogonal polarizations.
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.
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/m^2/per steradian).
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.

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]

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
CONOPS	Concept of Operations
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
LDPC	Low-density parity check
LSB	Least Significant Bit
MI	Modulation Index
MGMT	Management
MSB	Most Significant Bit
NR	New Radio
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
OPSCON	Operations Concept
OSI	Open Systems Interconnection
PRBS	Pseudo-Random Binary Sequence
PS	Preamble Sequence
RX PHY	Receiver Physical

RX_TS	Receiver Timestamp
S2A	Space-to-air
S2G	Space-to-ground
S2M	Space-to-maritime
S2S	Space-to-space
S2T	Space-to-terrestrial
SDA	Space Development Agency
SNR	Signal-to-noise Ratio
T0	Tranche 0
T1	Tranche 1
T2	Tranche 2
TX PHY	Transmitter Physical Layer
TX_TS	Transmit Timestamp
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 low earth orbit (LEO) space for S2S links and through a turbulent atmosphere for space-to-terrestrial (S2T) links. The atmosphere affects FSOC links in two ways:

- The atmosphere absorbs a portion of the light, resulting in a range-dependent attenuation of the signal
- 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 signal-to-noise ratio (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 (PAT) sequence follows the PAT State Machine defined in [3].

Requirement OCT-010: The OCT shall provide the pointing, acquisition, and tracking (PAT) functionality as defined in this section (2.1 Pointing, Acquisition, and Tracking (PAT)).

2.1.1 PAT Introduction

The PAT spatial acquisition shall be referred to as a lead and follow strategy (referred to as master-slave in [3]).

The PAT approach below provides the state machine and parameters for a common Pointing, Acquisition and Tracking approach for OCTs employed by the Space Development Agency (SDA) 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 [3] and provide details not otherwise provided in [3] 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

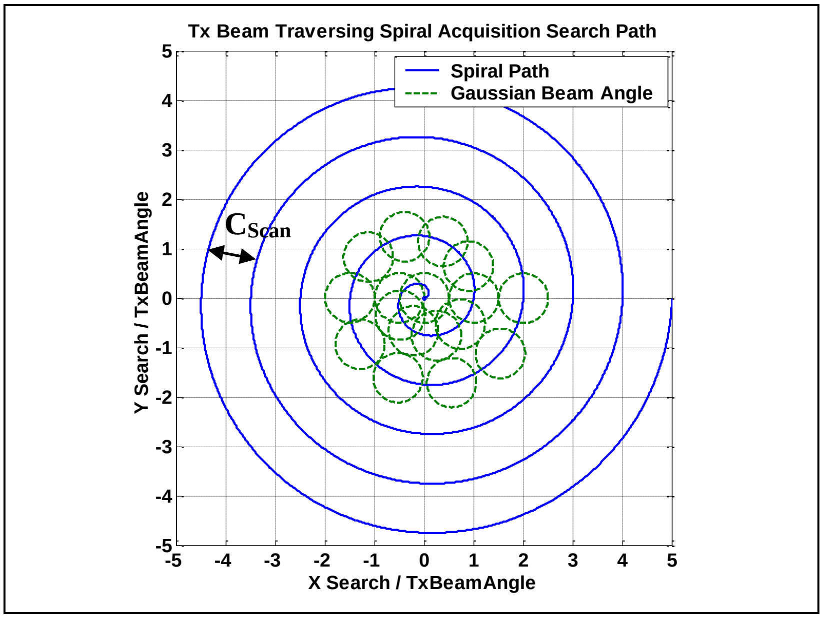

Figure 2-1. Spiral Scan Pattern

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 OCT implementations, 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 full-width at half maximum (FWHM) diameter), then the *OverlapLoss* = 3 dB, however, the spiral scan will take 1.7^2 = 2.9x longer.

2.1.3 Interoperable Pointing, Acquisition, and Tracking

Modeling the PAT sequence as an event-driven finite-state-machine provides a common model for all SDA OCT 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

In the state machine diagram below, the current time is t and the δ's represent the period of time that passes prior to timeout of the state.

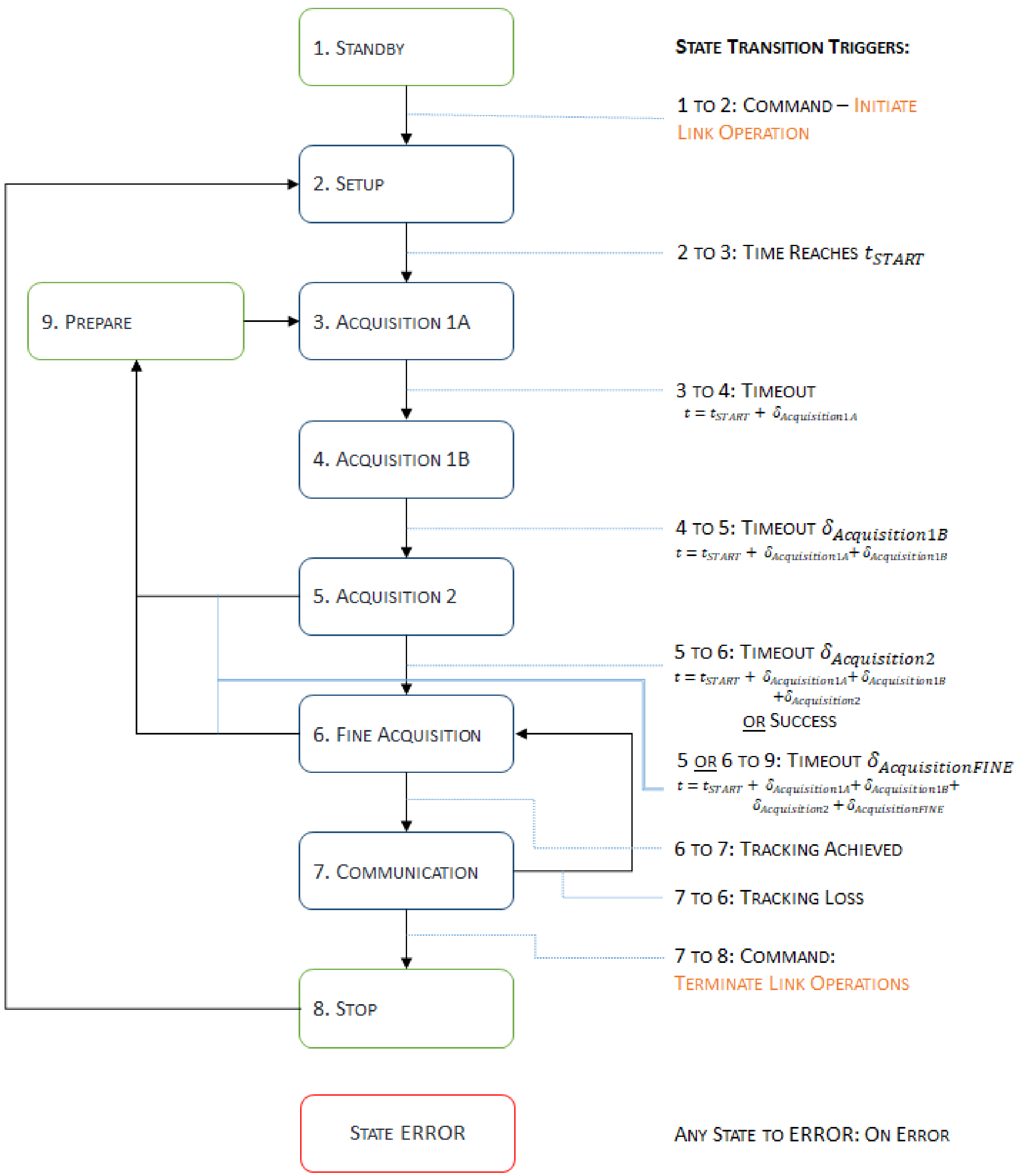

Figure 2-2. Interoperable PAT State Machine. In this figure, t is the current time.

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 **Required Parameters:** See Table 3	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 (both if systems are capable of simultaneous transmit and receive during acquisition) 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 provides the state machine configuration parameters. The range of values shall not be interpreted as requirements on the physical or mechanical capabilities of the system.

Table 2-2. State Machine Configuration Parameters

Parameter	Parameter Shorthand	Range of Values	Parameter Definition
Starting Uncertainty Cone (μrad)	TUC	0-65535	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)		0-65535	Spiral velocity compatible with receiver bandwidth of counter terminal. Set per-vendor.
Spiral Separation (*u*rad)		0-65535	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 OCT 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.
State Entry Time	t_{state}	This is the clock time at which the state was entered.

2.1.4 Acquisition Scheme

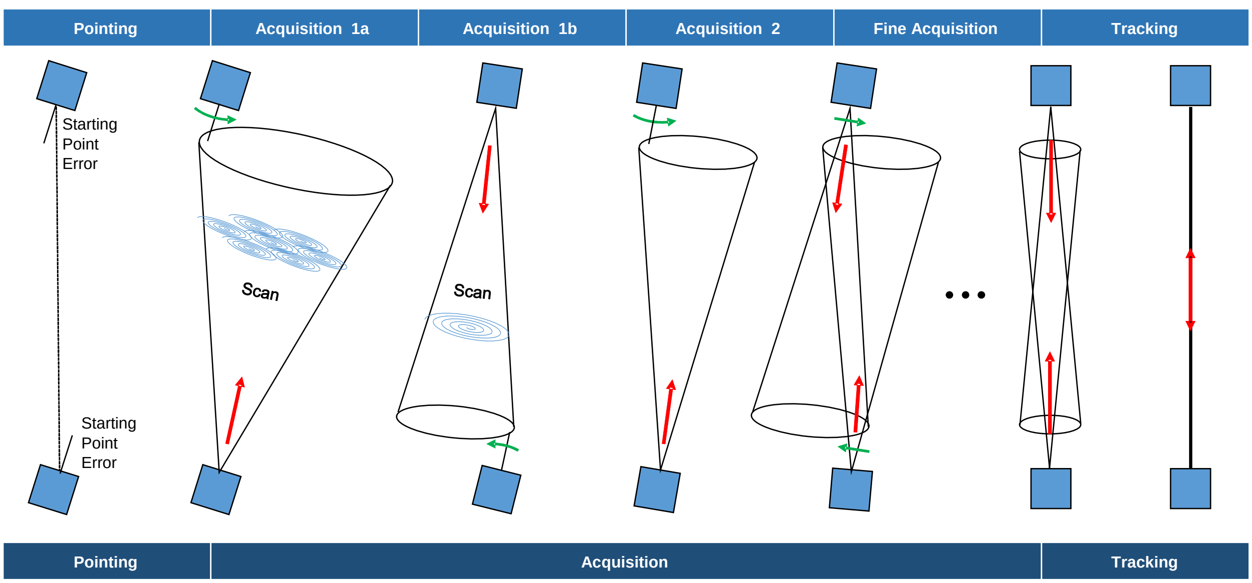

Figure 2-3. Spatial acquisition process diagramming the sub-states of pointing, acquisition, and tracking as defined within the PAT State Machine

Figure 2-3 shows the 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.

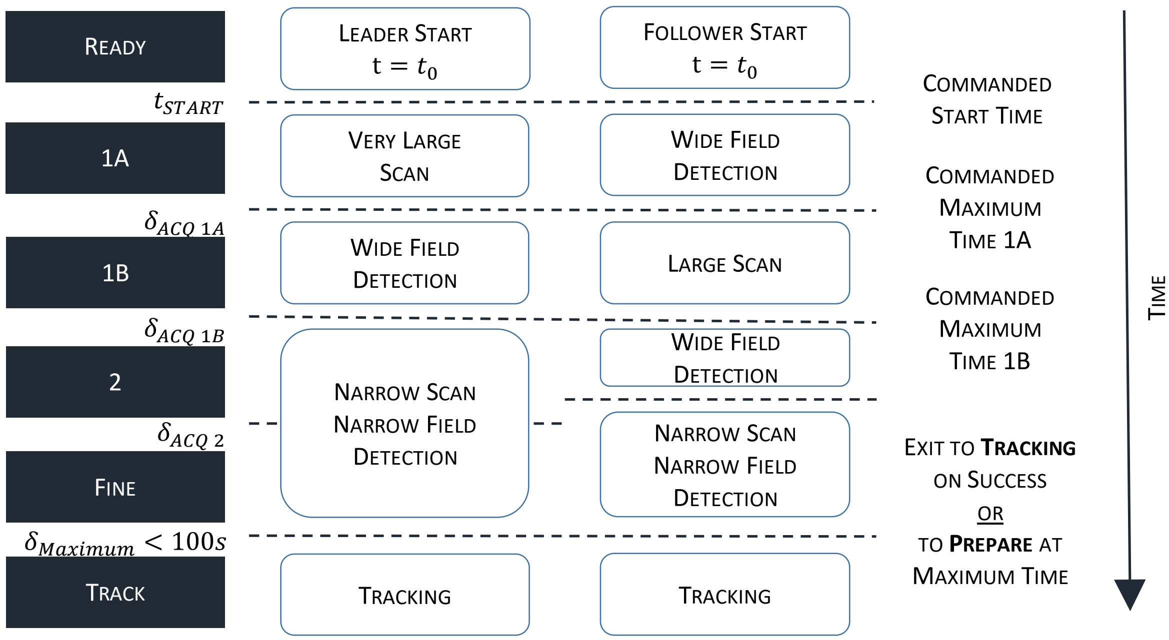

Figure 2-4. PAT Notional OPSCON. Time progresses from top to bottom. The transition from Acquisition 2 to Fine and Fine to Track is triggered by successful tracking. The definition of success for tracking is implementation-dependent. In this diagram, the Leader is depicted as having only a single field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

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 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.

2.1.5 Amplitude Modulation of Signals

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

$$MI = \frac{(Pmax - Pmin)}{(Pmax + Pmin)} \qquad \textit{Equation 1}$$

Figure 2-5 illustrates a notional sinusoidal tone along with the two associated power levels, Pmin and Pmax, used in the definition of MI.

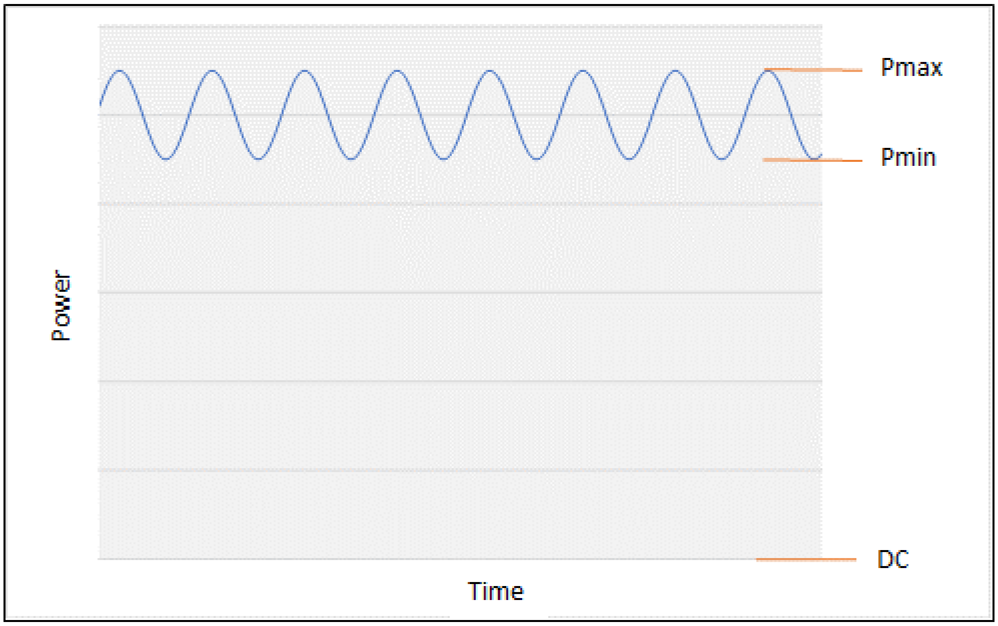

Figure 2-5: AM Tone Tracking Modulation. Pmin and Pmax are the power levels that define the modulation index (MI).

Requirement OCT-011: The OCT shall provide the described AM Tracking Tone.

Requirement OCT-012: The AM Tracking Tone shall be a sinusoid with selectable, via software command, 40 kHz and 50 kHz frequencies.

Requirement OCT-013: The OCT shall reference the amplitude of the transmitted signal to the minimum and maximum amplitude of the transmitted signal to the Modulation Index (MI).

Requirement OCT-014: The OCT shall provide the following selectable modulation indices: 0% (MI = 0 = modulation off), 10% (MI = 0.1), 20% (MI = 0.2), and greater than or equal to 80% (MI >= 0.8 AND MI <= 1). For all MIs greater than 0%, the error in MI shall be no greater than 20%.

Requirement OCT-015: The OCT's shall provide, via software command, the capability to set and get the modulation index of the AM tone.

2.1.6 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.

Definitions:

- ***Cold start*** means the post-calibration acquisition of a remote terminal where the TUC is sufficiently large such that Phase 1 of the PAT state machine **cannot** be bypassed.
- ***Warm start*** means the post-calibration acquisition of a remote terminal where the TUC is sufficiently small such that Phase 1 of the PAT state machine **can** be bypassed.
- ***Calibration*** means the set of activities required to quantify the relationship between the spacecraft and OCT coordinate systems.

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.

Requirement OCT-016: The OCT shall achieve a PAT Acquisition Time of $\leq 100\ seconds$ for a Cold Start.

> **Note on Requirement OCT-016:** This PAT Acquisition Time shall be applicable to any post-calibration PAT activity including the PAT Sequence/State Machine defined herein as well as any modified or alternative PAT Sequence employed by the OCT.

Requirement OCT-017: OCT Calibration shall result in a TUC sufficiently small for the PAT State Machine to close links under the conditions imposed by the OCT's design and operating environment.

> **Note:** Conditions imposed by the OCT's design and operating environment include, but are not limited to, transmitter parameters (e.g. beam divergence, power, beam quality, jitter, etc.), receiver parameters (e.g. receiver sensitivity, aperture diameter, jitter, , etc.), spacecraft contributions (e.g. thermal, mechanical, etc.), and environmental (e.g. solar load, background signals, etc.).

2.2 Modulation

The transmitter will provide Amplitude Modulated (AM) signals.

Requirement OCT-018: The OCT shall support Amplitude Modulation (AM) including OOK-NRZ and Manchester encoding.

2.3 Latency

The Receive Latency is defined as the duration of time from the first photon of a message arriving at the OCT through the exit of the reconstituted Ethernet packet from the OCT to the host spacecraft.

Requirement OCT-019: The OCT shall achieve a receive latency of no greater than 15 ms.

The Transmit Latency is defined as the time between entry of an Ethernet packet from the host spacecraft to the OCT through the transmission of the last photon of that packet.

Requirement OCT-020: The OCT shall achieve a transmit latency of no greater than 15 ms.

Requirement OCT-021: The OCT transmit and receive latencies shall, in the cases of S2G, S2A, or S2M links, be extended by the fadeout time due to atmospheric conditions and the ARQ retransmit time.

> **Note:** The fadeout times for S2G links will vary depending on atmospheric conditions. Fadeout times are the period of time in which atmospheric effects reduce the SNR below the required threshold for communications.

2.4 Spectral Grid Definition

To permit operations of multiple communications channels through wavelength division multiplexing (WDM), the ITU-T G.694 [4] 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).

The channels are defined by

$$F_{Center}(n) = 193.100\,THz + n \times 100.000\,GHz \qquad \textit{Equation 2}$$

where n is the channel number. The width of each channel is 100.000 GHz.

Requirement OCT-022: The OCT shall comply with the spectral grid as described in this section.

Requirement OCT-023: The OCT shall accommodate all range rate effects (e.g. Doppler, clock frequency deviations, etc.) for S2S in-plane and out-of-plane links, S2G, S2A, and S2M links.

Requirement OCT-024: The OCT receiver shall accommodate signals from transmitters within this channel scheme.

2.5 Transmit and Receive Wavelength

Table 2-4 defines 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 2-4. Channel definitions.

Channel Number (n)	Frequency (THz)	Wavelength (nm)
-1	193.100	1553.33
20	195.100	1536.61

Requirement OCT-025: The OCT shall provide the capability to transmit communications and PAT signals on the channels corresponding to those defined in this section.

Requirement OCT-026: The OCT shall provide the capability to receive communications and PAT signals on the channels corresponding to those defined in this section.

2.6 Channel Selection

Requirement OCT-027: The OCT shall provide, via software command, the capability to *set* and *get* the selected channel for both transmit and receive.

2.7 Polarization

Requirement OCT-028: The OCT's receiver shall accommodate random, time-varying polarization state.

2.8 Transmitted Signal and Receiver Interoperability

This Standard is intended to promote interoperability between makes and models of OCTs. In order to achieve compatible designs, the transmitted signal properties are described in this section. The transmitted signal must ultimately result in an irradiance at the receive aperture of sufficient stability for constant data transmission across the communications channel. Requirements described herein define a minimum viable product (MVP) for interoperability. It is required that, first and foremost, systems be interoperable.

Requirement OCT-029: OCT transmitters shall provide signals compatible with OCT Standard Compliant receivers.

Requirement OCT-030: OCT system engineering shall be performed to show, through link budget analysis, a margin of no less than 3 dB for like-designed systems for both the communications and PAT channels.

Requirement OCT-031: OCT system engineering shall be performed to show, through link budget analysis, a margin of no less than 3 dB for OCT-Standard-Compliant systems for both the communications and PAT channels.

Requirement OCT-032: OCT link testing shall demonstrate a margin of no less than 3 dB for like-designed systems for both the communications and PAT channels.

Requirement OCT-033: OCT link testing shall demonstrate a margin of no less than 3 dB for OCT-Standard-Compliant systems for both the communications and PAT channels.

> **Note:** The requirements in this section do not specify a range or geometry. The specified margin shall be achieved for any link within the ranges or geometries specified in this document.

2.8.1 Transmitted Signal Power

The full signal power within the channel provided at the plane of the receive aperture is defined as follows: the portion of the signal that remains after application of an ideal top-hat filter with width equal to the channel spacing and centered at the channel frequency.

Requirement OCT-034: The OCT shall provide, via software command, the capability to *set* and *get* the transmitted power. The minimum selectable transmitted power shall be 0 (zero). The maximum selectable transmitted power shall be the maximum transmitted power achievable by the system design.

Requirement OCT-035: The OCT shall achieve maximum transmitted power flux through the plane of the transmit aperture of no less than 2.5 W.

> **Note on Requirement OCT-035**: This requirement shall not be interpreted as an upper limit placed on the OCT's transmit power capability (e.g. systems capable of transmitting 5 W of power are compliant).

Requirement OCT-036: The OCT shall provide selectable transmit power, referenced at the plane of the transmit aperture) with levels spacing of no greater than 3 dB. The range of levels shall include 0 (zero) or "off." The range (not inclusive of "off") shall span from no greater than $1\mu W$ to the peak output power of the transmitter.

> **Note:** This range may be equivalently expressed as steps of 3 dB from -30 dBm (0.001 mW) to 33.97 dBm (2500 mW). The step size is permitted to be smaller than specified. The range is permitted to be wider than specified.

2.8.2 Notional Link Calculations

The link calculation example shown in Table 2-5 employs a 2.5 W transmitter with 10 cm optical beam director. The cases of “diffraction-limited” and “model” systems are shown. The model system uses a beam divergence of 3 times the diffraction limited beam divergence.

Note: This example is illustrative and is not intended to dictate design parameters.

Table 2-5 Transmitted beam example link budget.

Parameter	Diffraction Limited System	Model System	Units
Transmitted Power at Aperture	2.5	2.5	W
Wavelength	1.55E-06	1.55E-06	m
Transmit Aperture Diameter	0.1	0.1	m
Beam Divergence Multiplication Factor	1	3	
Beam Divergence	1.55E-05	4.65E-05	radians
Range	5500	5500	km
Beam Diameter at Range	85.25	255.75	m
Beam Area at Range	5707.93	51371.37	m^2
Irradiance at Range	4.38E-04	4.87E-05	W/m^2
Irradiance at Range	437.99	48.67	uW/m^2
Irradiance at Range with 3 dB Loss Allowance	219.0	24.3	uW/m^2

2.8.3 Transmitted Beam Requirements

Requirement OCT-037: The OCT shall be capable of producing an irradiance at the plane of a remote receive aperture at a range of 5,500 km of between 0 (zero) and no less than $25\ \mu W/m^2$. This irradiance at range shall be measured at the full-width at half maximum (FWHM) of the transmitted signal. The required irradiance value specified herein shall mean the mean signal crossing the plane of the aperture at range.

Note: Transmitters are permitted to provide transmitted powers above this range.

Requirement OCT-038: The OCT shall provide a transmitted beam of sufficient diameter (FWHM) at a ranges of >= 100 km to overfill a remote circular aperture of no less than 1.5 m and achieve a BER of $\leq 10^{-6}$ the in diameter in the absence of atmospheric effects and pointing error.

Requirement OCT-039: The OCT shall provide the required pointing control and provide a transmitted beam of sufficient diameter at a ranges of >= 100 km to overfill a remote circular aperture of no less than 0.15 m the in diameter (FWHM) and achieve a BER of $\leq 10^{-6}$ in the presence of pointing error.

Requirement OCT-040: The OCT shall provide the required pointing control and provide a transmitted beam of sufficient diameter at a ranges of >= 500 km to overfill a remote circular aperture of no less than 0.5 m in diameter (FWHM) and achieve a BER of $\leq 10^{-6}$ in the presence of atmospheric effects and pointing error.

2.8.4 Transmitted Power Safety Limit

Requirement OCT-041: The OCT shall provide, via software command, the capability to *set* and *get* the Transmitted Power Safety Limit (TPSL).

Requirement OCT-042: The OCT shall, under no circumstances, transmit power greater than the TPSL.

Requirement OCT-043: The *Default TPSL* shall be 0 (zero) W.

Requirement OCT-044: The OCT shall set the TPSL to the *Default TPSL* at system startup.

Requirement OCT-045: The TPSL shall only be modifiable by external command except upon system error. On system error, the TPSL shall be immediately set to the *Default TPSL.*

2.8.5 Background Noise Signal

The nominal day-in-the-life (DITL) background environment shall include all points in time for 24-hour period in which neither the sun nor moon is within 30 degrees of either the transmitter or receiver's boresight for a pair of in-plane optical terminals servicing a S2S, S2G, S2A, or S2M link of the specified range at an orbit of 80 to 82-degree inclination and 1000 km altitude.

Requirement OCT-046: Throughout the nominal DITL background environment, the receiver shall achieve sufficient SNR to operate at all modes defined in Table 3-2 and that remote transmitter is commanded to an appropriate transmission power within the range stated in this document.

2.8.6 Transmitted Signal Properties

The specification of pulse shape characteristics is made using an eye diagram mask. This section follows the prescription described in 7.2.2.14 of [5]. The pulse shape characteristics of the OOK-NRZ signals including rise and fall times, pulse overshoot and undershoot, and ringing are defined.

Requirement OCT-047: OCT transmitted signals shall comply with parameters defined through the eye diagram mask as defined in in section 7.2.2.14 of [5] with parameters described in Figure 7-3 of the same ("Mask of the eye diagram for NRZ optical transmit signals except ratio masks"). For the purpose of this requirement, the eye diagram mask defined by the "NRZ 10G 1550nm Region" column of the table in Figure 7-3 of [5] shall be used.

3 Layer 2 - Synchronization and Channel Coding Layer

This section defines the synchronization and channel coding layer for OCT Standard Complaint Systems. The current system employs a single protocol for S2S and S2T links. This protocol employs a Hybrid FEC ARQ approach for S2T channels. Within this protocol, the capability to turn both ARQ and FEC on or off is provided. For high signal-to-noise ratio (SNR) S2S channels, it is expected that ARQ will normally be "off" and FEC may be turned on or off based on the expected system and environmental conditions.

The 5G New Radio (NR) low-density parity check (LDPC) defined in [6] has been adopted as the primary FEC for SDA OCT Standard 3.

The Baud Rate and Code Rates in SDA OCT Standard 3.0.0 have been specified to provide S2S and S2T service with sufficient Ethernet packet throughput to provide continuous 1 Gbps bidirectional Ethernet communications both without and in the presence of atmospheric turbulence-induced channel fadeouts.

3.1 SDA OCT Standard 3 Protocol Classes

Table 3-1 lists the current SDA OCT Standard 3 protocols. This list may be appended with additional classes.

Table 3-1: SDA OCT Standard 3 Protocols

Name	Shorthand
SDA OCT Standard 3 - 3GPP 5G NR LDPC	SDA3-5GNR-LDPC

Requirement OCT-048: The OCT shall provide the protocol set listed in Table 3-1 for full-duplex transmit and receive.

3.2 Re-Programming

Requirement OCT-049: The OCT shall be reprogrammable on orbit. This shall include both protocol and all OCT software and firmware.

Requirement OCT-050: During reprogramming, links may be interrupted.

Requirement OCT-051: The OCT shall, via remote command, provide the capability to load new software (and firmware) as required to update, modify, or add protocols (not limited to protocols defined in Table 5) within the OCT's hardware capabilities.

3.3 Optical Signal Rates: Baud Rates and Encoding

Protocol Parameter Sets are grouped into Baud Rate categories

Table 3-2. SDA OCT Standard Protocol IDs and Baud Rates.

Protocol ID and Rate Designator (format: <Protocol ID>-<Optical Signaling Rate (GHz)>-<Encoding>)	Optical Signaling Rate	Baud Rate	Encoding
SDA3-5GNR-LDPC-2500-Manchester	2.5 GHz	1.25 Gbps	Manchester
SDA3-5GNR-LDPC-2500-OOK-NRZ	2.5 GHz	2.5 Gbps	OOK-NRZ

Requirement OCT-052: The OCT shall be capable of transmitting and receiving in full duplex at the rates and encodings defined in Table 3-2 with 100% operational duty cycle.

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 3-3.

Requirement OCT-053: 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 Cyclic Redundancy Check (CRC)) then a variable number of parity bits. The number of parity bits is governed by the configured codec and code rate (Section 3.4.4.1).

Table 3-3: Modem Frame Format

Field	# of bits	Comments
Preamble	64	Preamble: 64'53225b1d0d73df03. The MSB (64^{th}) bit is transmitted first followed in order down to the LSB (1^{st}).
Header	960	See Section 3.4.2.1.
Payload - Data	8448	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-054: 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 3-3.

3.4.2 Preamble Sequence

Requirement OCT-055: Every frame shall start with a Preamble Sequence (PS), which is used by the receive modem for frame synchronization.

Requirement OCT-056: The preamble sequence shall be identical for all OCT modem frames and takes the value shown in Table 3-3.

3.4.2.1 Header

Requirement OCT-057: A modem header shall be present in every modem frame immediately following the preamble sequence.

Requirement OCT-058: 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 3.4.3.2)
- The payload of the modem header is protected by a CRC-16 (Section 3.4.3.1).

The contents of the OCT modem frame header are detailed in Section 3.4.4.

3.4.2.2 Payload

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

3.4.2.2.1 Data Bits

Requirement OCT-059: All modem frames shall carry a payload of exactly 8448 information bits.

3.4.2.2.2 CRC-32

Requirement OCT-060: All modem frames shall protect the integrity of the payload information bits with a 32-bit CRC (Section 3.4.3.1).

3.4.2.2.3 Parity Bits

The OCT modem features strong payload FEC.

Requirement OCT-061: 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 can be as few as zero bits (uncoded) up to as many as 8448 bits (LDPC, code rate 1/2).
- The payload FEC is a quasi-cyclic low-density parity check (QC-LDPC) code defined in [6].

3.4.2.3 Scrambling

Requirement OCT-062: 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 6. The following describe the sequence employed in the generation of the scrambling sequence:

- The shift-register is initialized to $[x_0, x_1, \dots, x_{14}] = [000011011011100]$ 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 6 generates a scrambling sequence with period $2^{15} - 1 = 32767$ bits.

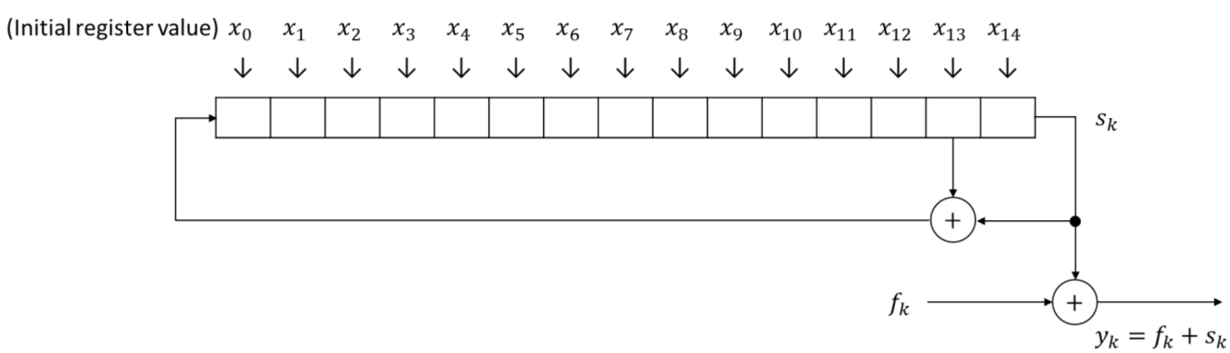

Figure 6: Generation of Scrambling Sequence

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 7 depicts the steps for frame generation.

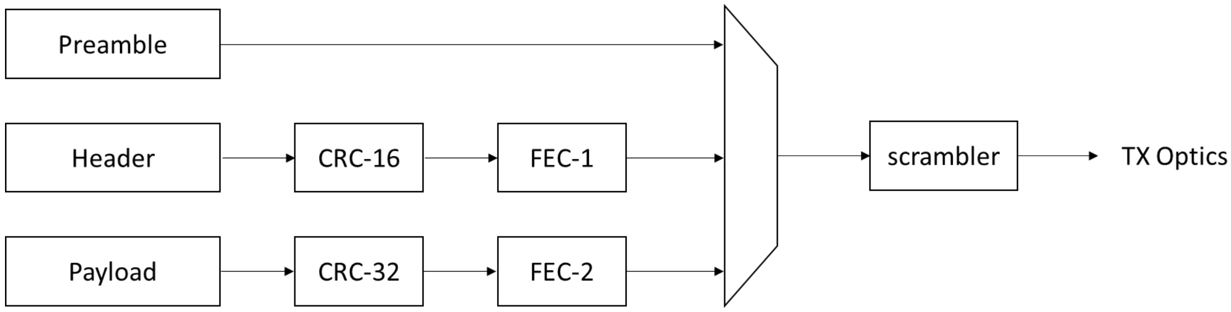

Figure 7: OCT modem Frame Construction

All frame types (Section 3.4.5) are constructed identically.

3.4.3 Error Control Coding

Requirement OCT-063: 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 3.4.3.1, header: 16 bits, payload: 32 bits)
- Fixed-rate convolutional code (CC) for the frame Header (Section 3.4.3.2)
- 5G NR Block 1 LDPC for the frame Payload (Section 3.4.3.3).

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

3.4.3.1 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 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 3-4 for each of the two CRC's required to create the modem frame.

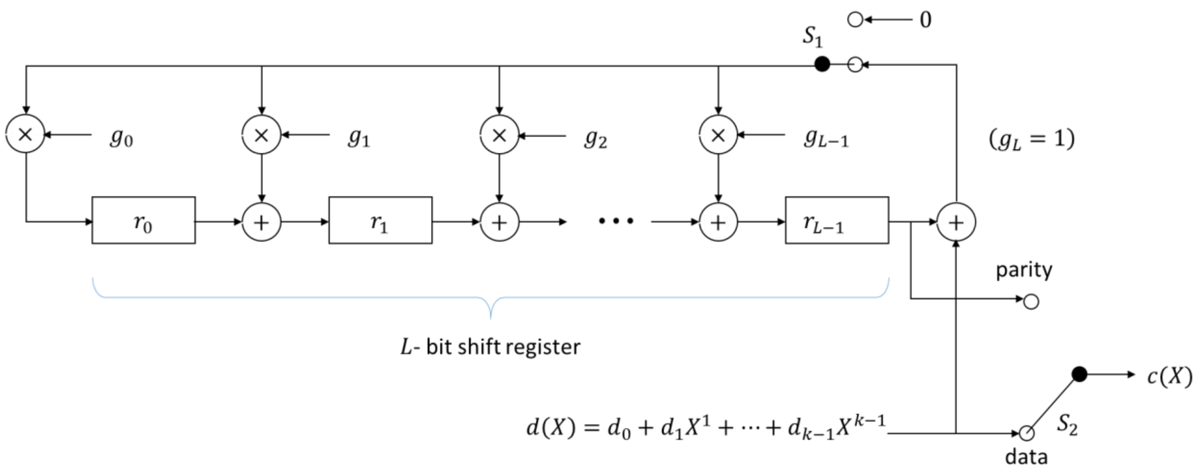

Figure 8: L-bit CRC Calculation Circuit

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 3-4: 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

3.4.3.2 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 3-5.

Table 3-5: 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 $160 \times 6 = 960$ bits.

3.4.3.3 Payload FEC

All OCT modem frames carry an 8448-bit payload per frame which is protected by both a CRC-32 and by an LDPC FEC.

The 5G NR User LDPC code is described in 5.2.2.2 of [6]. Key parameters are defined in Table 3-6. LDPC Parameters.

Table 3-6. LDPC Parameters

Parameter	Value or Range	Notes
Base Graph	Base graph 1	bg=0
Lifting Factor (Z)	384	
Number of parity bits (mb)	4-46	$4 \leq mb \leq 46$
Information Block Size	8448	Z*Kb (Kb=22)
Base graph cyclic shift set (z_set)	1	a = 3
Lifting Factor Component (z_j)	7	Z = a*2^{z_J}
Scale factor index	0.75	sc_idx=12
Algorithm	Normalized Min-Sum	

3.4.4 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.

3.4.4.1 Header Fields

The frame Header fields are listed in Table 3-7: Frame Header Fields. A single Header is present in every modem frame.

Table 3-7: Frame Header Fields

AQR	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)
			1100-111: 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	4	0000: no parity bits
			0001: 1536 parity bits
			0010: 2688 parity bits
			0011: 4224 parity bits
			0100: 8448 parity bits
			0101-1111: reserved
MAC	FRAME_TYPE	2	00: IDLE
			01:DATA
			10:MGMT
			11: reserved
pseudo-range	TX_TS	40	TX time-stamp (frame egress)
Fast Control Channel	FCCH_OPCODE	4	time-multiplexed control signaling
	FCCH_PL	48	Payload contents depends on FCCH_TYPE
CRC	CRC-16	16	
Zero-tail	ZT	6	
Total		**160**	

3.4.4.1.1 Frame Sequence Numbers

The TX frame sequence number (TXFN) shall be incremented on every transmitted frame in link session without regard to the FRAME_TYPE.

3.4.4.1.2 Automatic Repeat Request (ARQ)

Header fields supporting implementation of the Automatic Repeat Request modem feature are grouped as the "ARQ" fields. 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 applied upon command. ARQ shall be used for space-to-ground links but may be utilized on other links if both terminals support ARQ.

Only DATA and MGMT frames are 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 3-8. When operating with ARQ "on," the receive terminal shall support these configurable ARQ parameters.

Table 3-8: ARQ Parameters

Parameter	Valid Range	Number of bits	Description
ARQ_HOLDOFF_NFRAMES	0,16,32,…4096 N x 16, N=0…2^8	8	Window size of ARQ shall be a multiple of 16. The maximum value is 16 times 2^8=4096. The value of ARQ_HOLDOFF_NFRAMES determines the hold off time: e.g. $256 \times 80\ \mu s$ = 20 ms 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.
ARQ_HOLDOFF_TIME	0-2500ms	12	Hold-off time between re-transmissions

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

The ACK/NAK field in the Frame Header shall be ignored unless ACK-valid is set to one. When ACK-valid is one, the ACK shall apply to the FSO 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 3.4.6.1.6) 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).

The implementation shall provision ARQ buffers for both TX and RX duplexes. The storage required shall support the effective number of frames per ARQ cycle multiplied by the configured maximum number of retransmissions.

Sample calculations for the maximum supported link distance as a function of the configured parameter ARQ_HOLDOFF_NFRAMES are illustrated in Table 2-12.

Table 3-9: Sample Calculations for ARQ Max Link Distance

ARQ_ HOLDOFF_ NFRAMES	Effective NFRAMES	Round Trip Supported TOF (msec) by Baud Rate (Mbaud)			Link Distance (km) by Baud Rate (Mbaud)		
		312.5	625	1250	312.5	625	1250
1	16	1.277	0.638	0.319	191.508	95.754	47.877
16	256	20.428	10.214	5.107	3064.136	1532.068	766.034

160	2560	204.276	102.138	51.069	30641.357	15320.678	7660.339

The effective number of frames in a single ARQ cycle is ARQ_HOLDOFF_NFRAMES $\times$16. The time required to transmit all the frames in a single ARQ cycle is computed as the effective number of frames multiplied by the frame duration at the configured baud rate. The deadline for an ACK/NAK to be received from the far-end modem for a previously transmitted FSO frame is exactly the time required for the modem to TX all the frames in a single ARQ cycle. Therefore, the ARQ_HOLDOFF_NFRAMES parameter, along with the modem processing time, determines the supported link distance.

Sample time intervals for three baud rates and three values of ARQ_HOLDOFF_NFRAMES of interest are pre-computed in the Table 2-12. The time required to transmit the effective number of frames in a single ARQ cycle is labelled "Supported TOF." The ideal link distances corresponding to the computed TOF at the speed of light in a vacuum (3×10^8 m/sec) are tabulated in the table assuming an ideal modem (i.e., zero processing time). The link distance calculation should be modified in a practical implementation by subtracting the modem processing time from the supported TOF. In other words, the ARQ deadline is the "Supported TOF" column of the table. That time budget is shared by both propagation at the speed of light and modem processing delay.

3.4.4.2 Payload FEC

The OCT modem features strong payload FEC (Section 3.4.3.3).

Table 3-10: Payload FEC Code Rates (LDPC)

PL_RATE	Number of parity bits	Payload Code Rates (LDPC)
0	0	N/A
1	1536	0.8462
2	2688	0.7586
3	4224	0.6667
4	8448	0.5000

3.4.4.2.1 Timestamps

In support of external ranging and time transfer calculations, the OCT is required to provide frame timestamps indicating the egress time from the plane of the transmit aperture and ingress time at the plane of the receive aperture.

For frames transmitted by the OCT, the OCT is required to record and report the timestamps. This is in addition to populating the timestamp in the header of the outgoing frame. For frames received by the OCT, the OCT is required to record and report both time-of-transmit timestamps from the received frame as well as time-of-receipt timestamps measured locally. The OCT is required to record and report up to an integer number of frames (TS_RECORD_FRAMES) per second.

Requirement OCT-064: The OCT shall apply a timestamp in the header of every modem frame (TX_TS field, TOD_SECONDS).

- 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 implementation shall compensate timestamp (as required) for systematic time delays due to propagation paths outside the over-the-air connection between a pair of terminals.
- The TS-applies header bit indicates if the TS applies to current frame (0) or preceding frames (1-7).

Requirement OCT-065: The OCT shall record the timestamp from the header of transmitted modem frames and provide these to the host..

Requirement OCT-066: The OCT shall record the timestamp from the header of received modem frames and provide these to the host..

Requirement OCT-067: The OCT shall record and the ingress time of received modem frames and provide these to the host..

> **Note:** The means for calibrating path delays and compensating timestamp biases is implementation dependent.

Requirement OCT-068: The OCT shall aggregate, match to the frame specified by TX_NUM, and label with the corresponding frame identifier,

Requirement OCT-069: The OCT shall report the recorded timestamp information via the network interface.

> **Note:** The format of the timestamp report is implementation specific.

Requirement OCT-070: The OCT shall record timestamp information at a rate of TS_RECORD_FRAMES per second. The OCT shall be capable of a TS_RECORD_FRAMES of no less than one per second.

> **Note:** Timestamps of frames other than those required to be recorded and reported may be dropped.

Requirement OCT-071: The reports shall be at a frequency TS_REPORT_FREQUENCY in Hz. The OCT shall be capable of a TS_REPORT_FREQUENCY of no less than 1 Hz.

Requirement OCT-072: Timestamps shall be accurate to within 3 ns of the host’s clock.

3.4.4.3 Fast Control Channel (FCCH)

Requirement OCT-073: The OCT modem frame shall provide an embedded fast control channel (FCCH) as described herein.

The OCT 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 OCTs. 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.

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 3-11: FCCH Logical Channels**Error! Reference source not found.**. 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 3-11: FCCH Logical Channels

Description	FCCH_Type	Opcode (4 bits)	Message Rate (Hz)
Link Quality Reports	LAPC_BLER_REPORT	0000	1 Hz
	LAPC_RSSI_REPORT	0001	1 Hz
	LAPC_SYNC_REPORT	0010	1 Hz
Reserved	RESERVED	0011	
OCT Reports	OCT_CAPABILITIES	0100	Link Acquisition
Link Quality Reports Expansion	LAPC_RSSI_FAST	0101	100 Hz
Reserved	RESERVED	0110-1110	
Not Preset	N/A	1111	

The payload for each FCCH message shall be 16 bits. Payloads for each of the FCCH_TYPES are defined in Table 3-12.

Table 3-12: FCCH

FCCH_TYPE	Field	Bits	Description
LAPC_BLER_REPORT (Opcode = 0000)	LAPC_RPT_PL_BLER	16	number of payload CRC errors (trailing 1 sec from 1 PPS)
LAPC_RSSI_REPORT (Opcode = 0001)	LAPC_RPT_PIF_MEAN	8	Received power mean (average, trailing 1 sec from 1 PPS, step size=-0.25 dBm)
	LAPC_RPT_PIF_SDEV	8	Received Power standard deviation (average, trailing 1 sec from 1 PPS, step size=-0.25 dBm)
LAPC_SYNC_REPORT (Opcode = 0010)	LAPC_RPT_FS_LOSS	14	number of times frame sync lost (trailing 1 sec from 1 PPS)

	LAPC_RPT_FS_STATE	2	frame sync status (at 1 sec sample time)
			00: not locked
			01: locked
			10-11: reserved
OCT_CAPABILITIES (Opcode 0100)	PROTOCOL_VERSION	3	future expansion
	reserved	13	
LAPC_RSSI_FAST (Opcode = 0101)	LAPC_RPT_RSSI_FAST	14	Received Signal Power An LSB of <= 75 nW/m² (equivalent irradiance at target) is required. 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	Frame sync status, last 10 msec.
			00: not locked
			01: locked
			10: reserved
			11: reserved

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_BLER_REPORT, LAPC_RSSS _REPORT and LAPC_SYNC_REPORT shall be sent at rate at least 1 Hz.

OCT_SENSITIVITY shall be sent once after link acquisition and is used by the receiving terminal to control transmit optical power based on LAPC_RSSI_REPORT messages.

The OCT_CAPABILITIES is for future use for autonomous OCT Link configuration.

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

3.4.5 Special Frames

Requirement OCT-074: The FRAME_TYPE field of the frame 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.

3.4.5.1 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.

3.4.5.1.1 Header Construction

Modem IDLE frames are signaled in the frame header by field FRAME_TYPE=00.

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.

3.4.5.1.2 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 6) except with its initial seed equal to the value of the TXFN field in the frame header. 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 different value for its seed. Specific implementations shall document and publish the seed value selection method for this case.

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

3.4.5.2 MGMT Frames

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

3.4.5.2.1 Header Construction

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

3.4.5.2.2 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.

3.4.6 Ethernet Encapsulation

3.4.6.1 Overview of Ethernet Packet Encapsulation

Requirement OCT-075: The OCT data plane shall encapsulate Ethernet packets as Free Space Optical (FSO) frames for transport across the optical link as described herein.

The process is illustrated in Figure 9.

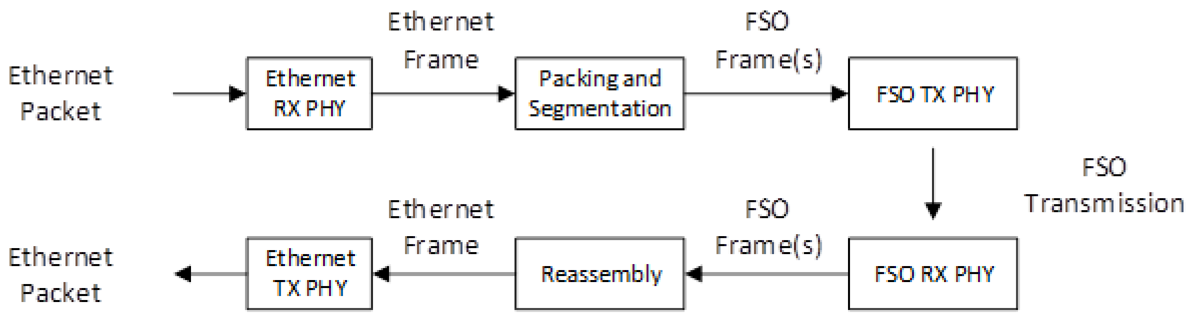

Figure 9: Ethernet Encapsulation

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.

3.4.6.1.1 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.

3.4.6.1.2 Packing and Segmentation

The *Packing and Segmentation* operation (Figure 9) 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

3.4.6.1.3 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 10. The bytes must be written into the payload FEC frame in physical byte order. The bytes must be consecutive, per word in Figure 10, 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 10.

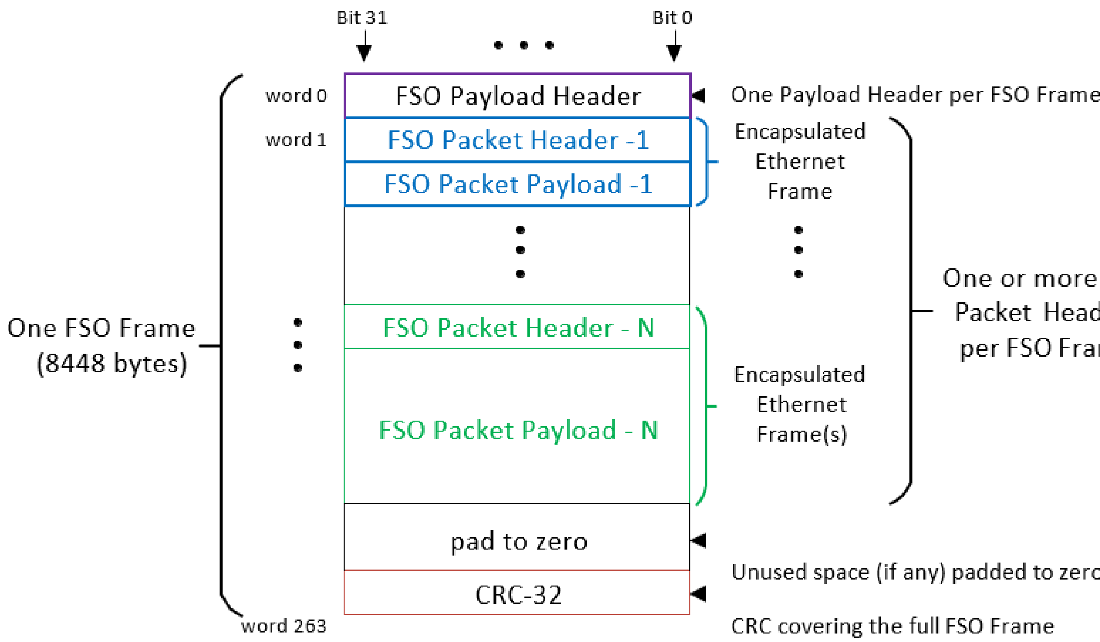

Figure 10: FSO Payload Frame Format

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 10.

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

3.4.6.1.4 FSO Payload and Packet Headers

Requirement OCT-076: Every FSO frame shall start with an FSO Payload Header.

Requirement OCT-077: There shall be exactly one FSO Payload Header (32 bits) per FSO frame.

Requirement OCT-078: The contents of the FSO frame and packet headers shall follow the definition presented in Table 3-13.

Table 3-13: 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 3-13 is unrelated to the modem's ARQ signaling.

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 3-13) 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.

3.4.6.1.5 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 10) 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 3-14. The Payload Header (Table 3-13) 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 3-14: 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 3.4.6.1.4).

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.

3.4.6.1.6 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 9) 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 3-13) is incorrect shall be discarded entirely.
- Any FSO Packet Header within any FSO frame (Table 3-13) whose magic number is incorrect shall be discarded.
- Any FSO Packet Header whose length field is inconsistent shall be discarded.

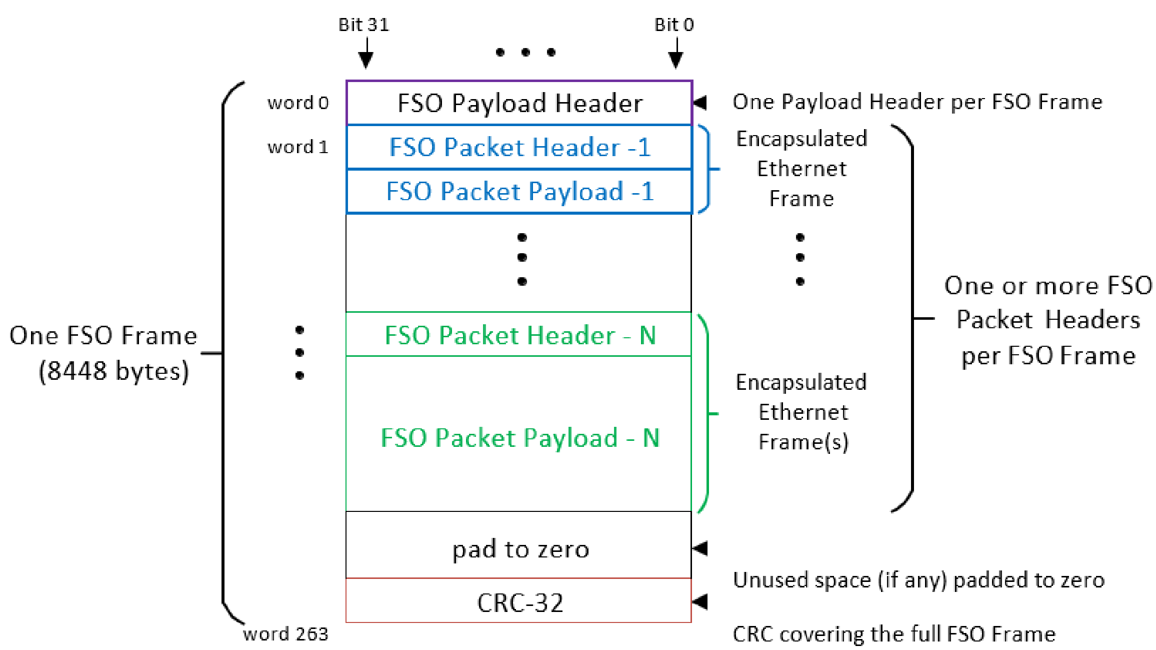

Figure 11: FSO Payload Frame Format

3.4.7 Effective Data Rate

Table 3-15Table 3-15: Effective Data Rates for Frame Configurations summarizes the frame configurations, pertinent metrics, and the resulting data rates for each.

Table 3-15: Effective Data Rates for Frame Configurations

Baud Rate (Mbps)	Line Code	PL RATE	LDPC Code Ratio	Preamble (bits)	Header (bits)	Payload (bits)	Parity (bits)	Optical Signaling Rate (MHz)	Baud Time (ns)	Frame Duration (us)	Max Theoretical Payload Data Rate (Mbps)	FCCH Data Rate	FCCH Data Rate (Mbps)
2500	None	0	0.00000	64	960	8448	0	2500	0.40	3.7888000	2221.28	12668919	12.67
2500	None	1	0.84615	64	960	8448	1536	2500	0.40	4.4032000	1911.34	10901163	10.90
2500	None	2	0.75862	64	960	8448	2688	2500	0.40	4.8640000	1730.26	9868421	9.87
2500	None	3	0.66667	64	960	8448	4224	2500	0.40	5.4784000	1536.21	8761682	8.76
2500	None	4	0.50000	64	960	8448	8448	2500	0.40	7.1680000	1174.11	6696429	6.70
1250	Manchester	0	0.00000	64	960	8448	0	2500	0.80	7.5776000	1110.64	6334459	6.33
1250	Manchester	1	0.84615	64	960	8448	1536	2500	0.80	8.8064000	955.67	5450581	5.45
1250	Manchester	2	0.75862	64	960	8448	2688	2500	0.80	9.7280000	865.13	4934211	4.93
1250	Manchester	3	0.66667	64	960	8448	4224	2500	0.80	10.9568000	768.11	4380841	4.38
1250	Manchester	4	0.50000	64	960	8448	8448	2500	0.80	14.3360000	587.05	3348214	3.35

3.4.8 LDPC Code Rates

The OCT modem implementation supports the four payload FEC code rates listed in Table 3-16.

Table 3-16: Payload FEC Code Rates

PL Rate	Total Size (Bits)	Parity Check (Bits)	Actual Code-Rate Ratio	(4 ≤ mb ≤ 46)	Z	Information Block size (Bits)
1	9984	1536	0.8462	4	384	8448
2	11136	2688	0.7586	7	384	8448
3	12672	4224	0.6667	11	384	8448
4	16896	8448	0.5000	22	384	8448

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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.

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