# Optical Communications Terminal (OCT) Standard Version 3.2.0

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# APPROVAL ROUTING

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## Summary of Changes to Enumerated Requirements

| 3.1.0 Section | 3.2.0 Section | 3.1.0 Req. Num. | 3.2.0 Req. Num. | 3.1.0 Text | 3.2.0 Text | Change Notes |
|---|---|---|---|---|---|---|
| 1.3.1.1 | | OCT-007 | OCT-007 | OCT Standard Compliant systems shall perform the PAT process without access to real-time side-channels for communications and coordination. 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. | OCT Standard Compliant systems shall perform the PAT process without access to real-time side-channels for communications and coordination. This acquisition process must be synchronous. Real-time OCT-to-OCT 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. | Removed obsolete bigraph. |
| 2.1.5 | | OCT-012 | OCT-012 | The AM Tracking Tone shall be a sinusoid with selectable, via software command, 40 kHz and 50 kHz frequencies. | The AM Tracking Tone shall be a sinusoid with selectable, via software command, 40 kHz and 50 kHz frequencies with a modulation frequency accuracy of at least 500 ppm. | Adds frequency accuracy component. |
| 2.1.5 | | ~ | OCT-083 | ~ | The modulation index of the AM tone shall be capable of predetermined variations as a function of state machine phase. This may include high (80%, MI $\geq 0.8$ & MI $\leq 1$) MI for acquisition scans through phase 2 with a transition to lower MI during and after the Fine Acquisition phase. MI is expected to remain static during the communication/track phase. | New Requirement |
| 2.1.6 | | OCT-016 | OCT-016 | The OCT shall achieve a PAT Acquisition Time of $\leq 100$ *seconds* for both Cold Starts and Warm Starts. | The OCT shall achieve a PAT Acquisition Time of $\leq$ 100 seconds for both cold starts and warm starts. Note on Requirement OCT-017: 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. | Clarifies when the 100 seconds timeline starts. |
| ~ | | ~ | OCT-084 | ~ | The OCT communications channel shall be synchronized to the OCT clock. | New Requirement |

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| 2.3 | ~ | 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. | The OCT transmit and receive latencies shall, in the cases of S2S, S2G, S2A, or S2M links, be extended by the ARQ window size and maximum number of retransmissions when ARQ is enabled . The fadeout times for S2G links will vary depending on atmospheric conditions. Fadeout times are the time periods in which atmospheric effects reduce the SNR below the required threshold for communications. | Not a testable requirement |
| 2.4 | | OCT-024 | OCT-024 | The OCT receiver shall provide the capability to transmit communications and PAT signals from transmitters within this channel scheme. | The OCT receiver shall provide the capability to receive communications and PAT signals from transmitters within this channel scheme. | Receiver receives, not transmits |
| 2.8.1 | | OCT-035 | OCT-035 | The OCT shall achieve maximum transmitted power flux through the plane of the transmit aperture of no less than 2.5 W. | The OCT shall achieve maximum transmitted power flux through the plane of the transmit aperture of no less than 2.5 W while concurrently meeting all other requirements stated in this standard. | Clarifies that all requirements must be met at high-power levels |
| 2.8.1 | | OCT-038 | OCT-038 | The OCT shall be capable of producing an irradiance at the plane of a remote receive aperture greater than or equal to 25 $\mu W/m2$ at a range of 5,500 km of. The required irradiance value specified herein is defined as the mean signal crossing the plane of the aperture at range when considering all flight-like affects such as platform jitter. | The OCT shall be capable of producing an irradiance at the plane of a remote receive aperture greater than or equal to 25 $\mu W/m2$ at a range of 5,500 km. The required irradiance value specified herein is defined as the mean signal crossing the plane of the aperture at range when considering all flight-like effects such as platform jitter and pointing error. | Typos; inclusion of pointing error |
| 2.8.1 | | OCT-040, OCT-041, OCT-042 | OCT-040 | Requirement OCT-040: The OCT shall provide a transmitted beam of no less than 1.5 meters in diameter (FWHM) at a ranges of ≥ 100 km and achieve a BER of ≤ 10−6 in the absence of atmospheric effects and pointing error.<br>Requirement OCT-041: The OCT shall provide the required pointing control and provide a transmitted beam of sufficient diameter, as defined in Requirement OCT-040, at a ranges of ≥ 100 km and achieve a BER of ≤ 10−6 in the presence of | The OCT shall provide a transmitted beam with a FWHM divergence of no less than 15 µrad. | Simplified overly prescriptive requirements into divergence requirement |

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|---|---|---|---|---|---|---|
| | | | | pointing error.<br>Requirement OCT-042: The OCT shall provide the required pointing control and provide a transmitted beam of no less than 0.5 meters in diameter (FWHM) at a ranges of ≥ 500 km and achieve a BER of ≤ 10−6 in the presence of atmospheric effects and pointing error. | | |
| ~ | | ~ | OCT-085 | ~ | When ARQ is enabled, the OCT shall apply the ARQ operation and retransmit any DATA and MGMT frames for which it does not explicitly receive an ACK back up to ARQ_MAX_RETX number of times. | New Requirement |
| ~ | | ~ | OCT-086 | ~ | When ARQ is enabled, the OCT shall apply ACK to DATA and MGMT frames received successfully. | New Requirement |
| 3.4.6.2.1 | | OCT-069 | OCT-069 | The OCT shall collect the ingress time of received modem frames and provide these to the host for TWTT/PNT processing. | The OCT shall collect the ingress time of received modem frames and provide these to the host for TWTT/PNT processing. The received timestamp refers to the time, expressed in the host's clock, at which the start of the frame enters the receive aperture. The start of the frame is defined as the beginning of the first symbol period of the frame. | Clarified timestamp. |
| 3.4.6.2.1 | | OCT-070 | OCT-070 | The OCT shall provide the valid TWTT timestamps from the MGMT frame to the host for TWTT/PNT processing from each MGMT frame received and matched to the corresponding frame specified by TS-applies. | The OCT shall provide the valid TWTT data from the MGMT frame to the host for TWTT/PNT processing from each MGMT frame received. | Clarified requirement. |
| ~ | | ~ | OCT-082 | ~ | The OCT shall populate the FCCH messages with valid data and use frame sync status in the LAPC_RSSI_FAST message to determine communication state. | New Requirement |

# Table of Contents

# 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) links.

This OCT Standard is intended to enable interoperability between optical communication terminals where at least one endpoint is a space-based terminal.

## 1.1 Requirements

Requirements in this document take two forms:

1. Normative text stating **'shall' or 'must'** which **indicates a binding and verifiable specification.**
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>

**Requirement OCT-001**: OCT Standard Compliant Systems shall implement all normative and enumerated requirements in this document.

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

Note: The term *OCT Standard Compliant* denotes an OCT System that fully implements the OCT-to-OCT interface **and** those requirements (directly stated, derived, implied, or otherwise) on the external systems for the duration of the expected system lifetime. OCT Standard Compliant OCT Systems are interoperable with other systems within the same Major Version.

**Requirement OCT-002**: OCT Standard Compliant Systems shall implement derived requirements as needed to enable successful operations and to ensure interoperability.

**Note on Requirement OCT-002:** Space vehicle and OCT system vendors shall determine derived requirements through their individual systems engineering and design processes.

## 1.2 Compliance with the OCT Standard

### 1.2.1 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 compliant free-space optical communication (FSOC) systems.

**Requirement OCT-003:** OCT Standard v3.2.0-compliant systems shall be interoperable with other OCT Standard 3.*.*-compliant systems, with version compliance as described in **Requirement OCT-006**.

### 1.2.2 Errata, Bug Reports, Clarifications, and Modification Requests

**Requirement OCT-004:** 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.

### 1.2.3 Version Control

**Requirement OCT-005:** OCT Standard-compliant systems shall document the list of OCT Standard versions and modes with which they are compliant.

**Requirement OCT-006:** 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 Release
- Major Release Number
  - Major Releases change significant functionality. OCT Systems compliant with a Major Release shall be interoperable with OCT Systems compliant with the same Major Release. Compatibility between different Major Releases is not guaranteed.

Compliance with this version of the OCT Standard is documented as "Compliant with SDA OCT Standard 3.2.0".

## 1.3 Elements of the OCT Standard

This document provides descriptions of two Open System Interconnection (OSI) Model [3] 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 [4])

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

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

- Mechanical interfaces to the spacecraft bus
- Telemetry, Tracking and Control (TT&C) System

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

### 1.3.1 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.

#### 1.3.1.1 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-007:** OCT Standard Compliant systems shall perform the PAT process without access to real-time side-channels for communications and coordination.

This acquisition process must be synchronous. Real-time OCT-to-OCT 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 reference time.

**Requirement OCT-008:** OCTs shall have a real-time clock synchronized to absolute time (the OCT Clock).

**Note:** 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-009**: OCTs shall provide the capability to reference real-time events (e.g., timers, delays, triggers, events, etc.) to the OCT Clock.

Systems in motion, such as the OCTs used on spacecraft and aircraft, must each track their remote counterpart 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 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.

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

### 1.3.2 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).

## 1.4 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 channel symbols per second. |
| **Bit Numbering Convention** | The convention used to identify each bit in an N-bit field will conform to Section 3.4. |
| **Bit Rate** | The number of bits conveyed per unit of time. Default unit of time: seconds. |
| **Channel Capacity** | The theoretical upper bound for the maximum net bit rate, 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] |
| **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 $100x10^6$ bps or $10^8$ bps. |
| **Decoded Bit-Error Rate** | The number of bit errors after applying Forward Error Correction. |
| **Extinction Ratio** | Extinction ratio is the ratio of transmitted logical levels. |
| **Field of Regard (FOR)** | The field of regard is the total 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.<br>The solid angle may be expressed in steradians or, equivalently, as a cone angle. FOVs for rectilinear sensors may be represented the rectangular cone angles. Circular cone angles may represent circular sensors, inscribed or circumscribed rectilinear sensors, circularly symmetric optical systems, etc.<br>Descriptions must be specified for specific FOVs to communicate the solid angle and geometry being represented.<br>See also HFOV and FFOV. |
| **Frame Error Rate** | The ratio of number of frames received in error after FEC to the total number of transmitted frames. |
| **Full Field of View (FFOV)** | The expression for FOV specified by the diameter (angular or spatial) of the FOV or the half-angle for a general cone. |

| Term | Definition |
|---|---|
| **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 time-averaged (over a period much greater than the bit period) radiant flux through a measurement plane 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 bit rate of the physical layer of a communications channel. *Line Rate* may also be referred to as the "raw bit rate," "data signaling rate," "gross data transfer rate," or "uncoded transmission rate." [4] |
| **Modulation** | 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)** | 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 the total number of transmitted Ethernet packets. |
| **Pseudo-Random Binary Sequence** | A pseudorandom binary sequence (PRBS) is a binary sequence that, while generated with a deterministic algorithm, is difficult to predict and exhibits statistical behavior like a truly random sequence. |
| **User Rate** | The net bit rate 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 |
| **CoM** | Center of Mass |
| **CRC-16** | Cyclic Redundancy Check with a 16-bit polynomial |
| **DCE** | Data Circuit-terminating Equipment |
| **DTE** | Data Terminal Equipment |
| **DWDM** | Dense WDM |
| **eTWTT** | Enhanced Two-Way Time Transfer |
| **FCCH** | Fast Communications Channel |
| **FEC** | Forward Error Correction |

| Acronym | Meaning |
|---|---|
| **FFOV** | Full Field of View |
| **FOV** | Field of View |
| **FSOC** | Free-Space Optical Communications |
| **GEP** | Ground Entry Point |
| **HDR** | High Data Rate |
| **HFOV** | Half Field of View |
| **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 |
| **NAK** | Negative Acknowledgement |
| **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 |
| **SC** | SpaceCraft |
| **SDA** | Space Development Agency |
| **SNR** | Signal-to-Noise Ratio |
| **T0** | Tranche 0 |
| **T1** | Tranche 1 |

| Acronym | Meaning |
|---|---|
| **T2** | Tranche 2 |
| **T3** | Tranche 3 |
| **TOF** | Time Of Flight |
| **TWTT** | Two-Way Time Transfer |
| **TX PHY** | Transmitter Physical Layer |
| **TX_TS** | Transmit Timestamp |
| **WDM** | Wavelength-Division Multiplexing |

# 2 Layer 1 - Physical Layer

The Physical Layer as presented in this document 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:
  - Scintillation: variations in the signal intensity (and thereby the signal-to-noise ratio (SNR)) and position.
  - 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:

- Pointing, Acquisition, and Tracking (PAT)
- Communications

The PAT channel's purpose is to provide the required signals and motion control to align two terminals 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* [4]. 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 [4].

**Requirement OCT-010:** The OCT shall provide the pointing, acquisition, and tracking (PAT) functionality as defined in this OCT Standard.

### 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 [4]).

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 0 of [4] and provide details not otherwise provided in [4] 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

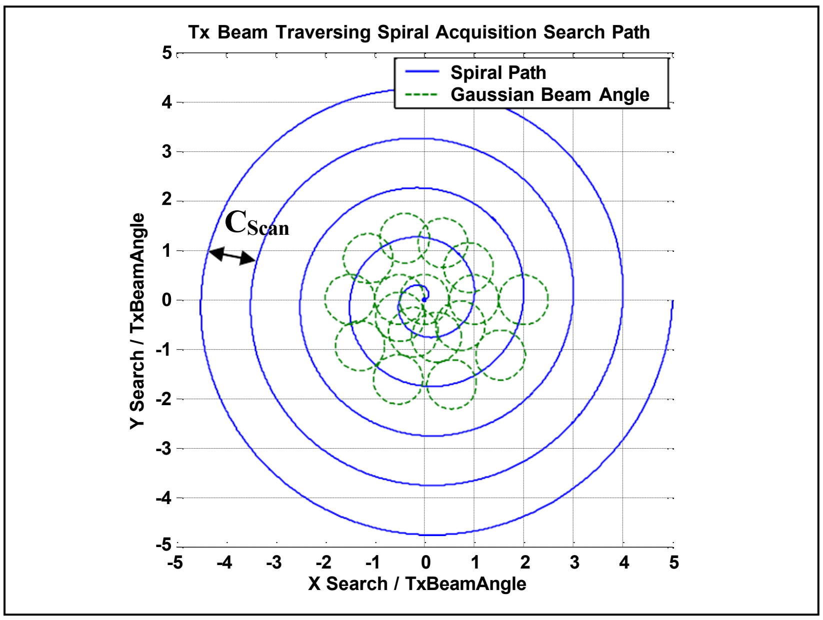


*Figure 2-1 Spiral Scan Pattern*

Figure 2-1 Spiral Scan Pattern 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:

$$T_{Spiral\ Scan} = \pi T_{Scan} \left(\frac{C_{Search}}{C_{Step}}\right)^2 \qquad \text{(Eq. 1)}$$

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:

$$P_{Tx} - BeamDivergenceLoss - BeamPointingJitterLoss - Margin - OverlapLoss > P_{Rx\_min} \qquad \text{(Eq. 2)}$$

The overlap loss term is related to the ratio of $C_{Step}$to the transmit $\frac{1}{e^2}$ beam divergence $\theta_{TX}$. 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 up-to-date 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 $\delta$'s represents the time that passes prior to timeout of the state.

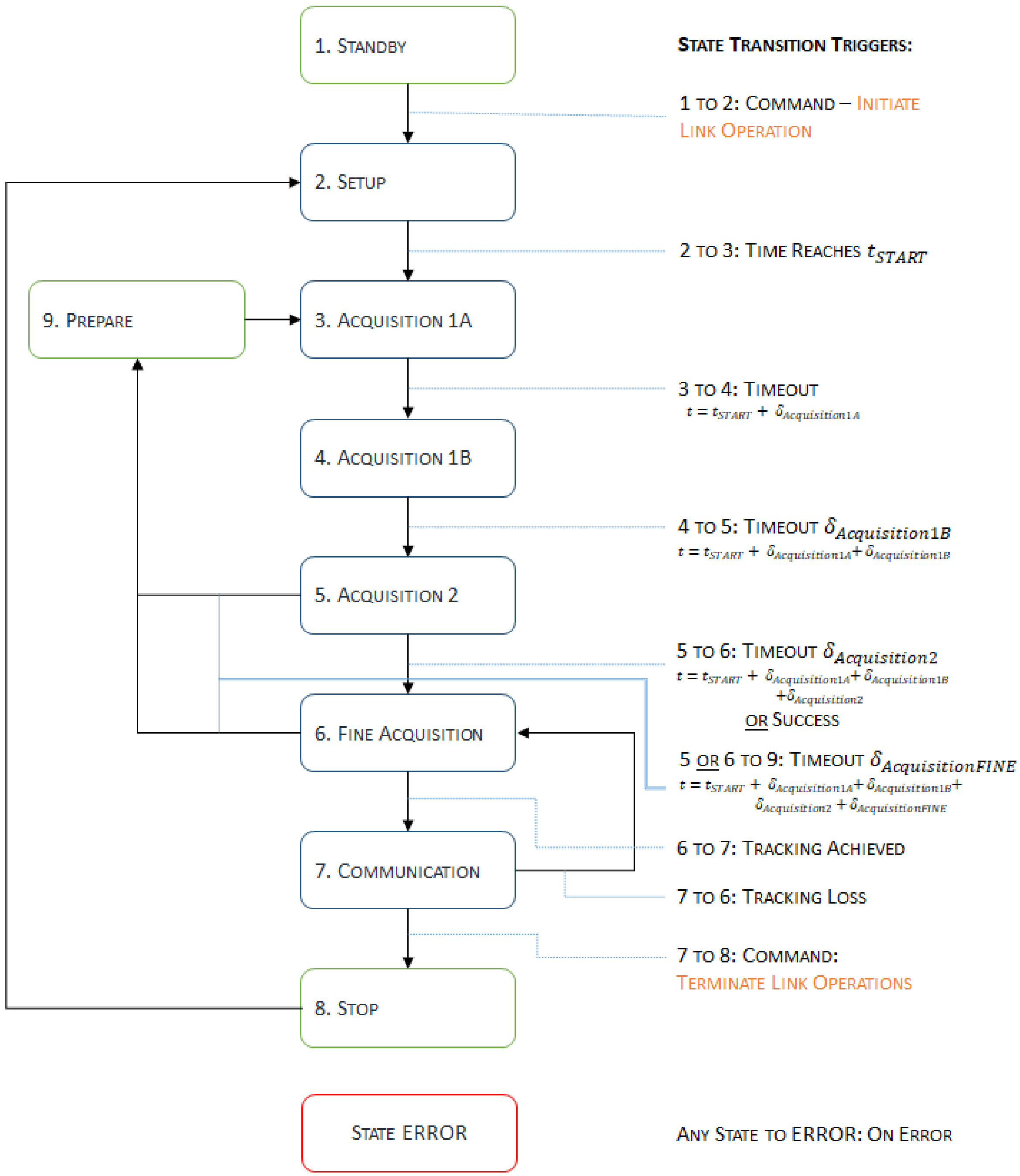


*Figure 2-2 Interoperable PAT State Machine. In this figure, t is the current time.*

*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 → Standby |
| **2** | **Standby** | 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<br><br>**Required Parameters:** See Table 2-2 | OCT has slewed into position and terminal has been configured ahead of $t_{START}$ being reached<br>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.<br>The follow OCT detects hits and performs pointing adjustments, reducing the level of starting uncertainty. | | Configuration Parameter Phase 1A duration reached ($\delta_{Acq1A}$)<br>→Acquisition Phase 1B |
| **4** | **Acquisition Phase 1B** | During acquisition phase 1B the follow OCT scans the remaining cone of uncertainty.<br>The lead OCT detects hits and performs pointing adjustments, reducing the level of starting uncertainty. | | Configuration Parameter Phase 1B duration reached ($\delta_{Acq1B}$)<br>→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.<br>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<br>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.<br>Timeout waiting to establish tracking → Prepare |
| **7** | **Communication** | Tracking achieved and bidirectional data link is established | | Command Received: $\delta_{LmtGoStop}$ → Stop<br>Tracking signal lost → Fine Acquisition |
| **8** | **Stop** | The link is terminated by command or due to a | | Laser and all mechanism stopped and |

| ID | Name | Description | Entry Criteria | Exit Criteria |
|---|---|---|---|---|
| | | failure condition. The OCT goes back to standby | | goes back to standby |
| **9** | **Prepare** | Prepare for reestablishing the link<br>Complete acquisition sequence is repeated using the configuration according to the latest Initiate Link Command with the next acquisition start time defined by:<br>$T_{NextAquisitionStart} = t_{START} + \Omega_{AcqPeriod} \cdot \left\lceil \frac{t - t_{START} + \delta_{AcqPreparation}}{\Omega_{AcqPeriod}} \right\rceil$<br>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 |

### 2.1.3.1.1 Configuration Parameters and Telemetry

Table 2-2provides 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 ($\mu rad$)** | 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)** | $\delta_{Acq1A}$ | 0-65535 | Duration of first spiral scanning phase (1A). Nominally symmetric across terminals, but terminal shall act as commanded. |
| **Phase 1B duration (seconds)** | $\delta_{Acq1B}$ | 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** | | -1 or 20 | TX wavelength selection, see Table 2-5. |
| **TX Tracking tone modulation** | | On or off | Determines if TX laser amplitude modulation used. |
| **TX Tracking tone modulation frequency** | | 40 or 50 kHz | Determines the rate of modulation of the AM tracking tone. |
| **Modulation Index of the TX Tracking tone** | MI | 0, 10, 20, and ≥80% | Modulation index is the ratio of the modulation excursions of a signal to the level of the unmodulated carrier. |
| **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 separation is defined as the pitch between adjacent spiral arms. |
| **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. |

| Parameter | Parameter Shorthand | Range of Values | Parameter Definition |
|---|---|---|---|
| **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 criterion 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 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.

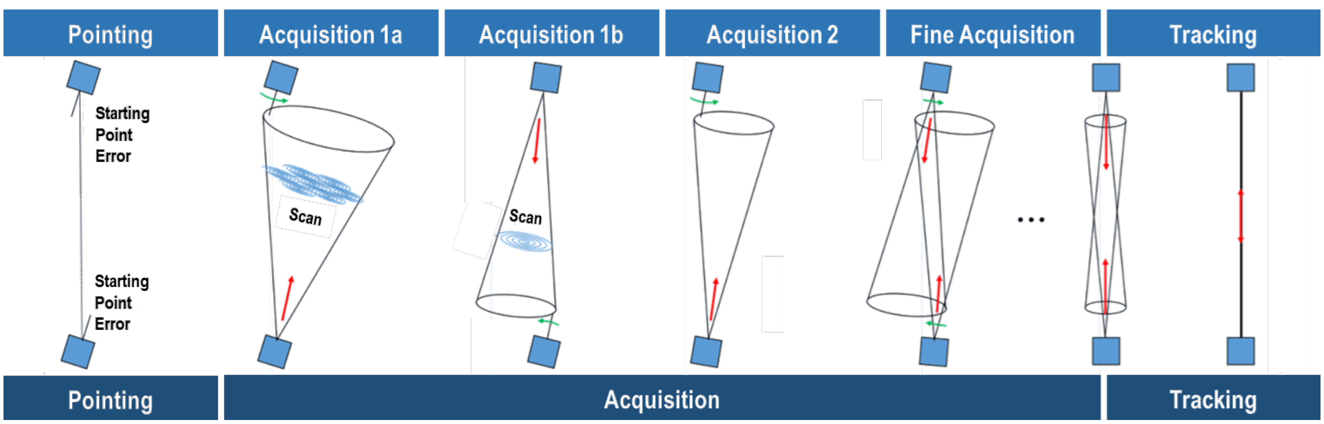


*Figure 2-3 Spatial acquisition process diagramming the sub-states of pointing, acquisition, and tracking as defined within the PAT State Machine.*

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

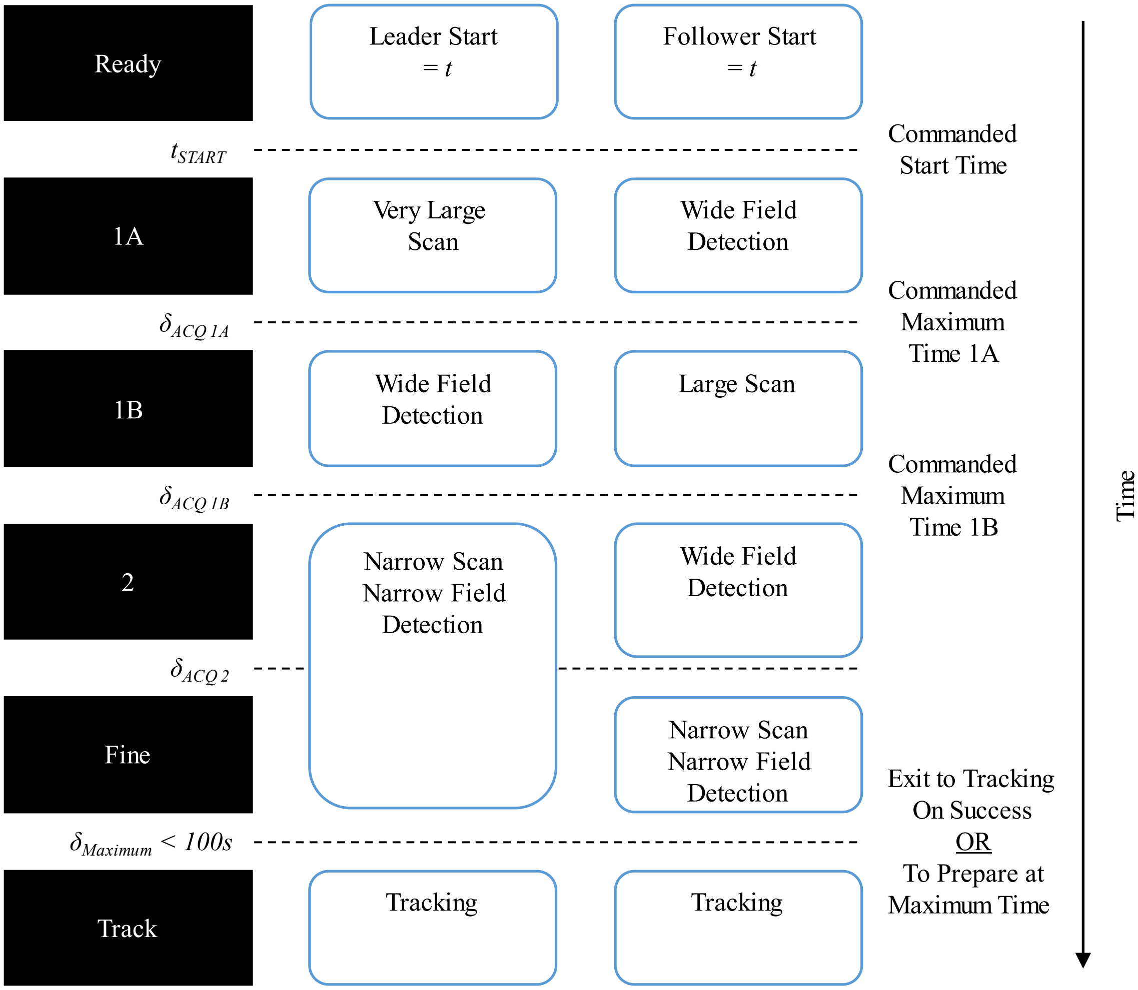


*Figure 2-4 PAT Notional OPSCON. Time progresses from top to bottom. The transition from Acquisition 2 to Fine and Fine to Track is triggered by successful tracking. The definition of success for tracking is implementation dependent. In this diagram, the Leader is depicted as having only a single field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

### 2.1.5 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:

$$MI = \frac{(P_{max} - P_{min})}{(P_{max} + P_{min})} \qquad (Eq.\ 3)$$

Figure 2-5 illustrates a notional sinusoidal tone along with the two associated power levels, $P_{min}$ and $P_{max}$, used in the definition of MI.

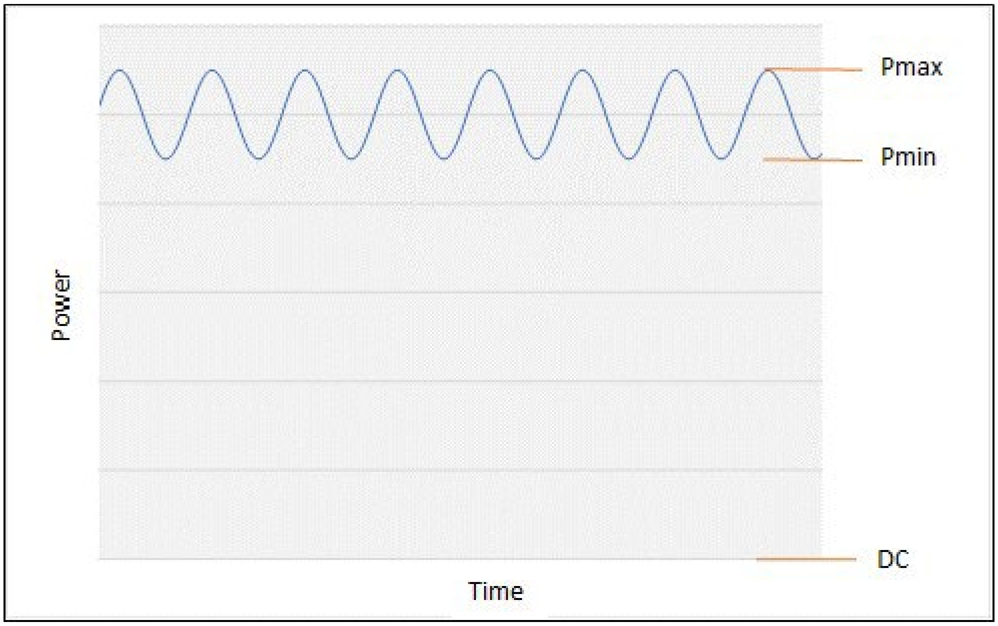


*Figure 2-5 AM Tone Tracking Modulation. Pmin and Pmax are the power levels that define the modulation index (MI).*

**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 with a modulation frequency accuracy of at least 500 ppm.

**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 tracking tone shall be no greater than 20%.

**Note on Requirement OCT-014:** 20% tracking tone error is described by the following metrics where $P_{mean}$ is the time-averaged mean power of the modulated signal:

- The minimum value of the tone ($P_{min}$) shall not go below $P_{mean}(1 - 1.2 \cdot MI)$
- The amplitude of the fundamental harmonic component shall be at least $0.8 \cdot P_{mean} \cdot MI$
- $P_{mean}$ shall achieve all transmitted power requirements described elsewhere in this standard.

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

**Requirement OCT-083:** The modulation index of the AM tone shall be capable of predetermined variations as a function of state machine phase. This may include high (80%, MI ≥ 0.8 & MI ≤ 1) MI for acquisition scans through phase 2 with a transition to lower MI during and after the Fine Acquisition phase. MI is expected to remain static during the communication/track phase.

### 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**:

- 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 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*.
- 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 ≤ 100 seconds for both cold starts and warm starts.

**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 on Requirement OCT-017:** 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 Amplitude Modulated (AM) signals follow the formats and conventions as described in this section.

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

**Requirement OCT-084:** The OCT communications channel shall be synchronized to the OCT clock.

For Manchester encoding, the convention implemented is given by Table 2-4 with transmission order of symbols being from left to right.

*Table 2-4 Manchester Encoding*

| Coded bit | Transmitted Symbol |
|---|---|
| 0 | {0, 1} |
| 1 | {1, 0} |

## 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.

**Note on Requirement OCT-019 and Requirement OCT-020:** The OCT transmit and receive latencies shall be extended by the ARQ window size and maximum number of retransmissions when ARQ is enabled. The fadeout times for S2G links will vary depending on atmospheric conditions. Fadeout times are the time periods in which atmospheric effects reduce the SNR below the required threshold for communications. This note replaces OCT-021 of SDA OCT Standard v3.1.0.

## 2.4 Spectral Grid Definition

To permit operations of multiple communications channels through wavelength division multiplexing (WDM), the ITU-T G.694 [5] 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:

$$F_{Center}(n) = 193.1\,THz + n \times 100.000\,GH \qquad \textit{(Eq. 4)}$$

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 provide the capability to receive communications and PAT signals from transmitters within this channel scheme.

## 2.5 Transmit and Receive Wavelength

Table 2-5 defines the transmit and receive wavelengths. Either channel may be used for transmitting while the other is used for receiving. The same channel may not be used simultaneously for send and receive.

*Table 2-5 Channel Definitions*

| Channel Number (n) | Frequency (THz) | Wavelength (nm) |
|---|---|---|
| **-1** | 193.000 | 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 receiver shall accommodate any and all received polarization states at the plane of the receive aperture.

**Note on Requirement OCT-028:** The OCT receiver must accomplish all requirements of this OCT Standard regardless of the polarization of the received signal. This OCT Standard does not restrict the polarization of the transmit signal and therefore each receiver must be able to accept any received polarization to enable interoperability.

## 2.8 Transmitted Signal and Receiver Interoperability

This Standard is intended to promote interoperability between makes and models of OCTs. 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 Signal Power

The full signal power within the channel provided at the plane of the receive aperture shall be defined as the portion of the signal that remains after application of an ideal top-hat filter with width equal to the channel width 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 while concurrently meeting all other requirements stated in this standard.

**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 output power shall be selectable between the minimum and maximum power output. The step size shall be no greater than 3 dB.

- The OCT's minimum power output is a key driver of the lowest operating range (the "minimum range"). Lower minimum power output permits closer ranges. The OCT shall have a minimum power output value of less than or equal to 40 mW.
- The OCT's maximum power output is a key driver of the highest operating range (the "maximum range"). Higher maximum power output permits longer ranges. The OCT shall have a maximum power output value of greater than or equal to 2.5 W.

**Note**: The transmitted power refers to the average power transmitted by the OCT as measured at the plane of the transmit aperture over a duration of at least 10,000 seconds of continuous stream IDLE frames in any and all modes at a constant set power level, within the constraints imposed by the eye diagram in Section 2.8.4.

**Requirement OCT-037:** The OCT shall limit the maximum irradiance delivered at the plane of the remote receive aperture to no more than 10 $mW/m^2$ at any established link distance.

**Note on Requirement OCT-037:** The OCT may limit the maximum provided irradiance by adjusting the output power based on the link distance.

**Requirement OCT-038:** The OCT shall be capable of producing an irradiance at the plane of a remote receive aperture greater than or equal to 25 $\mu W/m^2$ at a range of 5,500 km. The required irradiance value specified herein is defined as the mean signal crossing the plane of the aperture at range when considering all flight-like effects such as platform jitter and pointing error.

**Note on Requirement OCT-037 and Requirement OCT-038:** The OCT may control the delivered irradiance by adjusting output power based on link distance or feedback from the remote terminal.

**Requirement OCT-039:** The OCT receiver shall be capable of achieving a post-FEC BER $\leq 10^{-6}$

with an irradiance at the plane of the receive aperture of 25 $\mu W/m^2$ (as defined by **Requirement OCT-039**) at all required data rates.

**Requirement OCT-040:** The OCT shall provide a transmitted beam with a FWHM divergence of no less than 15 μrad.

**Note on Requirement OCT-040**: This requirement replaces the requirements OCT-040, OCT-041, and OCT-042 of the SDA OCT Standard v3.1.0.

### 2.8.2 Transmitted Power Safety Limit

**Requirement OCT-043:** The OCT shall provide, via software command, the capability to *set* and *get* the Transmitted Power Safety Limit (TPSL).

**Requirement OCT-044:** The OCT shall, under no circumstances, transmit power greater than the TPSL.

**Requirement OCT-045:** The *Default TPSL* shall be 0 (zero) W.

**Requirement OCT-046:** The OCT shall set the TPSL to the *Default TPSL* at system startup.

**Requirement OCT-047:** 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*.

### 2.8.3 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 and the background is consistent with the geometry of the S2S and S2T links.

**Requirement OCT-048:** Throughout the nominal DITL background environment, the receiver shall achieve sufficient SNR to operate at all modes defined in Table 3-2 when that remote transmitter is commanded to a transmission power within the range stated in **Requirement OCT-036**.

### 2.8.4 Transmitted Signal Properties

The specification of pulse shape characteristics is made using an eye diagram mask. This section follows the prescription described in Section 7.2.2.14 of [6]. The pulse shape characteristics of the OOK- NRZ signals including rise and fall times, pulse overshoot and undershoot, and ringing are defined.

**Requirement OCT-049:** OCT transmitted signals shall comply with parameters defined through the eye diagram mask as defined in in Section 7.2.2.14 of [6] with parameters described in Figure 7-3 of the same ("Mask of the eye diagram for NRZ optical transmit signals except ratio masks"). For this requirement, the eye diagram mask defined by the "NRZ 10G 1550nm Region" column of the table in Figure 8-3 of [6] shall be used.

**Note on Requirement OCT-049:** When Manchester encoding is used, the same eye diagram mask shall apply to each half-bit of the Manchester symbol.

# 3 Layer 2 - Synchronization and Channel Coding Layer

This section defines the synchronization and channel coding layer for OCT Standard Compliant 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 [7] has been adopted as the primary FEC for SDA OCT Standard 3.2.0.

The Baud Rate and Code Rates in SDA OCT Standard 3.2.0 have been specified to provide S2S and S2T service with sufficient Ethernet packet throughput to provide continuous bi-directional Ethernet communications up to 2.5 Gbps 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 3.2.0 Protocols*

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

**Requirement OCT-050:** The OCT shall provide the protocol set listed in Table 3-1 for full-duplex transmit and receive.

## 3.2 Re-Programming

**Requirement OCT-051:** The OCT shall be reprogrammable on orbit. This shall include both protocol and all OCT software and firmware.

**Note on Requirement OCT-051:** During reprogramming, links may be interrupted. This note replaces OCT-052 of SDA OCT Standard v3.1.0.

**Requirement OCT-053:** 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 3-1) within the OCT’s hardware capabilities.

## 3.3 Optical Signal Rates: Baud Rates and Encoding

### 3.3.1 Protocol Rates and Encodings Summary

Protocol Parameter Sets are grouped into Baud Rate categories. Protocol ID format given as:

<Protocol ID>-<Optical Signaling Rate (MHz)>-<Encoding>

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

| Waveform ID | Optical Signaling Rate (MHz) | Encoding | Baud Rate (Mbps) |
|---|---|---|---|
| **SDA3-5GNR-LDPC-2500-OOK-NRZ** | 2500 | OOK_NRZ | 2500 |
| **SDA3-5GNR-LDPC-2500-Manchester** | 2500 | Manchester | 1250 |
| **SDA3-5GNR-LDPC-1250-OOK-NRZ** | 1250 | OOK_NRZ | 1250 |
| **SDA3-5GNR-LDPC-1250-Manchester** | 1250 | Manchester | 625 |
| **SDA3-5GNR-LDPC-625-OOK-NRZ** | 625 | OOK_NRZ | 625 |
| **SDA3-5GNR-LDPC-625-Manchester** | 625 | Manchester | 312.5 |
| **SDA3-5GNR-LDPC-312.5-OOK-NRZ** | 312.5 | OOK_NRZ | 312.5 |
| **SDA3-5GNR-LDPC-312.5-Manchester** | 312.5 | Manchester | 156.25 |

**Requirement OCT-054:** 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-055:** 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 3.4.6.1).

*Table 3-3 Modem Frame Format*

| Field | # Of bits | Comments |
|---|---|---|
| **Preamble** | 64 | Preamble: 64’53225b1d0d73df03.<br>The MSB (64$^{th}$) bit is transmitted first followed in order down to the LSB (1$^{st}$). |
| **Header** | 960 | See Section 3.4.3. |
| **Payload - Data** | 8416 | Information payload. Fixed size 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-056:** 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-057:** Every frame shall start with a Preamble Sequence (PS), which is used by the receive modem for frame synchronization.

**Requirement OCT-058:** The preamble sequence shall be identical for all OCT modem frames and takes the value shown in Table 3-3.

### 3.4.3 Header

**Requirement OCT-059:** A modem header shall be present in every modem frame immediately following the preamble sequence.

**Requirement OCT-060:** 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 3.4.5.2)
- The payload of the modem header is protected by a CRC-16 (Section 3.4.5.1).

The contents of the OCT modem frame header are detailed in Section 3.4.6.

### 3.4.4 Payload

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

3.4.4.1.1 Data Bits

**Requirement OCT-061:** All modem frames shall carry a payload of exactly 8448 information bits.

3.4.4.1.2 CRC-32

**Requirement OCT-062:** All modem frames shall protect the integrity of the payload information bits with a 32-bit CRC (Section 3.4.3.1).

3.4.4.1.3 Parity Bits

The OCT modem features strong payload FEC.

**Requirement OCT-063:** 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 9216 bits (LDPC, code rate 1/2).
- The payload FEC is a quasi-cyclic low-density parity check (QC-LDPC) code defined in [7].

#### 3.4.4.2 Scrambling

**Requirement OCT-064:** 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:

$$x = 1 + x^{14} + x^{15} \qquad \text{(Eq. 5)}$$

The sequence can be generated by a linear-feedback shift-register circuit. A reference implementation producing the correct scrambling sequence is shown in Figure 3-1. The following describe the sequence employed in the generation of the scrambling sequence:

- The shift-register is initialized to a seed value of $[x_0, x_1, \ldots, x_{14}]$ = [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 3-1 generates a scrambling sequence with period $2^{15} - 1 = 32767$ bits.

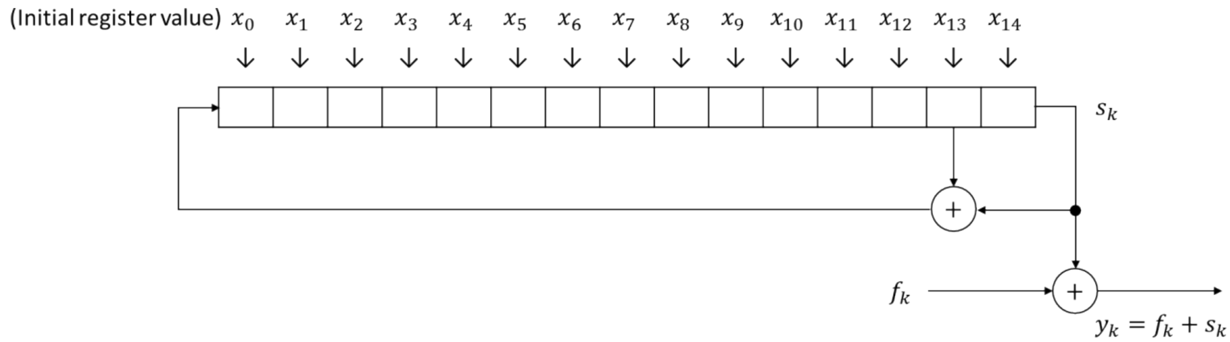


*Figure 3-1 Generation of Scrambling Sequence*

The modem starts preamble sequence application at the first bit of the header. The preamble sequence is not scrambled. The same scrambling seed is applied at the start of every modem frame. Figure 3-2 depicts the steps for frame generation.

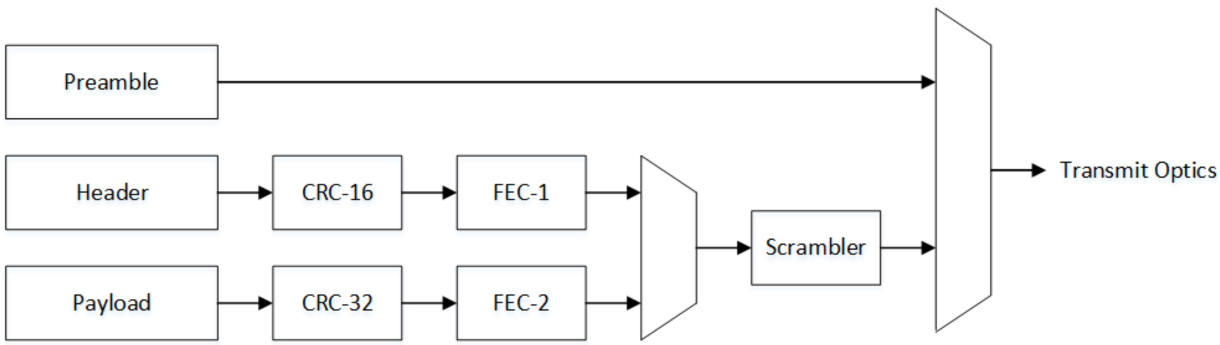


*Figure 3-2 OCT Modem Frame Construction*

All frame types (Section 3.4.7) are constructed identically.

### 3.4.5 Error Control Coding

**Requirement OCT-065:** 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 CRCs (Section 3.4.5.1, header: 16 bits, payload: 32 bits).
- Fixed-rate convolutional code (CC) for the frame header (Section 3.4.5.2).
- 5G NR Block 1 LDPC for the frame payload (Section 3.4.5.3).

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

#### 3.4.5.1 Cyclic Redundancy Checks

Two CRCs 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 3-3. The circuit consists of a $L$-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.

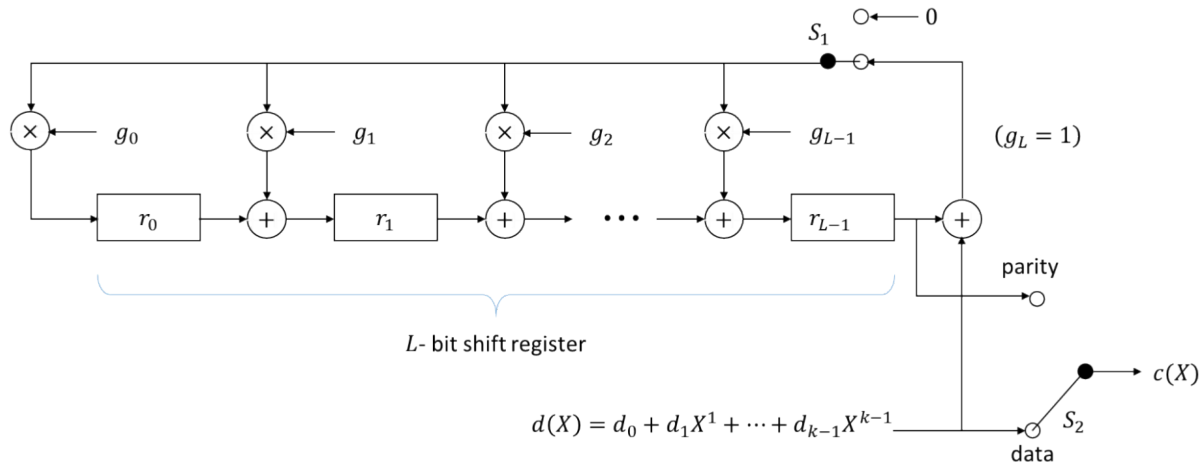


*Figure 3-3 L-bit CRC Calculation Circuit*

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

#### 3.4.5.2 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 header data structure is described in Section 3.4.4.

A 16-bit checksum is attached to the block of header information bits. 16 zero-valued pad bits are appended after the checksum to complete the CRC attachment and to initialize the convolutional encoder to zero state at the start of every new header.

For consistency with the bit ordering in the header, the encoding order for the header FEC is:

- First 8 information bits into the header FEC encoder: byte d0: bit 7, bit 6, bit 5, … , bit 0
- Second 8 information bits into the header FEC encoder: byte d1: bit 7, bit 6, bit 5, … , bit 0
- Bits are fed into the encoder (after CRC attachment and zero padding) until 20 bytes have entered the header FEC encoder.

The total size of the encoded header as transmitted "over the air" is 16×8+16+16=160 bits to be fed into the Header FEC encoder.

3.4.5.2.1 Transmission Order

Let $\{c_{k,5}, c_{k,4}, \dots, c_{k,0}\}$ be the 6 coded bits emitted by the convolutional encoder for the $kth$ input information bit, where $c_{*,n}$ is associated with the $nth$ code polynomial. Then, encoded header bits are transmitted in this order:

- First six coded bits corresponding to the first ($k$=0) information bit: $c_{0,5}, c_{0,4}, \dots, c_{0,0}$
- Next six coded bits corresponding to the second ($k$=1) information bit: $c_{1,5}, c_{1,4}, \dots, c_{1,0}$

### 3.4.5.3 Payload FEC

All OCT modem frames carry an 8416-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 of [7]. Key parameters are defined in Table 3-6.

Note: 5G NR LDPC punctures the first 768 bits of the information block which are offset by the generation of 768 additional parity bits.

*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 | |

### 3.4.6 Frame Header

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

#### 3.4.6.1 Header Fields

The frame header fields are listed in Table 3-7. A single header is present in every modem frame.

*Table 3-7 Frame Header Fields*

| Function | Field Name | Bits | Description |
|---|---|---|---|
| | TXFN | 16 | Sequence number of this (outgoing) TX frame |
| **ARQ** | 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=5) |
| | ARQ_NFRAMES | 8 | ARQ_HOLDOFF_NFRAMES |
| | ARQ_MAX_RETX | 3 | ARQ_MAX_RETX |
| **FEC** | PL_RATE | 4 | 0000: no parity bits |
| | | | 0001: 2304 parity bits |
| | | | 0010: 3456 parity bits |
| | | | 0011: 4992 parity bits |
| | | | 0100: 9216 parity bits |
| | | | 0101-1111: reserved |
| **MAC** | FRAME_TYPE | 2 | 00: IDLE |
| | | | 01: DATA |
| | | | 10: MGMT |
| | | | 11: reserved |
| **Transmit Timestamp** | TX_TS | 40 | TX timestamp (frame egress), number of picoseconds of whole second in time-of-day epoch: 0-999,999,999,999 |
| | TOD_SECONDS | 6 | Number of seconds in time-of-day epoch: 0-59 |
| | TS-applies | 3 | TX_TS applies to current frame (0), preceding frames (1-7) |
| **Fast Control Channel** | FCCH_OPCODE | 6 | Time-multiplexed control signaling |
| | FCCH_PL | 16 | Payload contents depends on FCCH_TYPE |
| **CRC** | CRC-16 | 16 | Frame header CRC defined in 3.4.5.1 |
| **Zero-Tail** | ZT | 16 | Zeroes used to flush the frame header CRC |
| **Total** | | 160 | |

TX_NUM is limited to five retransmission attempts due to ARQ_MAX_RETX.

The physical order in which the logical header fields shall be mapped is shown in Table 3-8.

*Table 3-8 Mapping of Logical Fields into Physical Order*

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

The CRC-16 bit ordering is consistent with the T0 implementation [1].

- First 8 information bits into the CRC-16: byte d0: bit 7, bit 6, bit 5, … , bit 0
- Second 8 information bits into the CRC-16: byte d1: bit 7, bit 6, bit 5, … , bit 0
- Bits are fed into the CRC-16 until 16 bytes have entered the computer with the last information bit being byte d15, bit 0.

This accounts for the processing of 16×8=128 information bits into the CRC-16 computer.

3.4.6.1.1 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.

3.4.6.1.2 Automatic Repeat Request (ARQ)

Header fields supporting implementation of the Automatic Repeat Request modem feature are grouped as the "ARQ" fields, as shown in Table 3-7.

**Requirement OCT-085**: When ARQ is enabled, the OCT shall apply the ARQ operation and retransmit any DATA and MGMT frames for which it does not explicitly receive an ACK back up to **ARQ_MAX_RETX** number of times.

**Requirement OCT-086**: When ARQ is enabled, the OCT shall apply ACK to DATA and MGMT frames received successfully.

**Notes on Requirement OCT-085 and Requirement OCT-086**: The ARQ functionality is enabled by setting ARQ_MAX_RETX to one or more. IDLE frames are not subject to ARQ. Successful reception of a frame is defined as the payload CRC-32 passing. Terminals for which an ACK is not explicitly received are treated as NAK'd.

The automatic repeat request scheme shall be configured with the set of parameters in Table 3-9. The ARQ configuration parameters shall only be changed prior to the onset of acquisition and remain static for the duration of a session. When operating with ARQ enabled, the OCT shall support these configurable ARQ parameters.

*Table 3-9 ARQ Parameters*

| Parameter | Valid Range | Number of bits | Description |
|---|---|---|---|
| **ARQ_HOLDOFF_NFRAMES** | 0, 16, 32, …, 4096<br><br>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.<br>The value of ARQ_HOLDOFF_NFRAMES determines the hold off time:<br>Window size and hold-off time are not set independently. |
| **ARQ_MAX_RETX** | 0-5 | 3 | Maximum number of retransmission attempts. |

When ACK_valid is one, the ACK shall apply to the FSO frame with sequence number RXFN; otherwise, the ACK/NAK shall be ignored. The OCT shall provision ARQ buffers for both TX and RX duplexes. The frame buffer storage required shall support the effective number of frames per

ARQ cycle multiplied by the configured maximum number of retransmissions. The effective number of frames in a single ARQ cycle is ARQ_HOLDOFF_NFRAMES ×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.

Correctly received FSO frames shall be released to the Ethernet reassembly block (Section 3.4.8.1.6) 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).

*Table 3-10 Sample Calculations for ARQ Max Link Distance*

| Baud Rate (Mbps) | Modulation | PL RATE | ARQ HOLDOFF FRAMES | Round Trip TOF (s) | Max. Supported Link Distance (km) |
|---|---|---|---|---|---|
| **1250.00** | Manchester | 4 | 1 | 0.000459 | 69 |
| **625.00** | Manchester | 4 | 1 | 0.000918 | 138 |
| **312.50** | Manchester | 4 | 1 | 0.001835 | 275 |
| **156.25** | Manchester | 4 | 1 | 0.003670 | 551 |
| **1250.00** | Manchester | 4 | 64 | 0.015099 | 2265 |
| **625.00** | Manchester | 4 | 64 | 0.058720 | 8808 |
| **312.50** | Manchester | 4 | 64 | 0.117441 | 17616 |
| **156.25** | Manchester | 4 | 64 | 0.234881 | 35232 |
| **1250.00** | Manchester | 4 | 128 | 0.030199 | 4530 |
| **625.00** | Manchester | 4 | 128 | 0.117441 | 17616 |
| **312.50** | Manchester | 4 | 128 | 0.234881 | 35232 |
| **156.25** | Manchester | 4 | 128 | 0.469762 | 70464 |
| **1250.00** | Manchester | 4 | 255 | 0.060162 | 9024 |
| **625.00** | Manchester | 4 | 255 | 0.233964 | 35095 |
| **312.50** | Manchester | 4 | 255 | 0.467927 | 70189 |
| **156.25** | Manchester | 4 | 255 | 0.935854 | 140378 |

Sample time intervals for three baud rates and three values of ARQ_HOLDOFF_NFRAMES of interest are pre-computed in the Table 3-10. 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 ($3 \times 10^8$ 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.

#### 3.4.6.1.3 Payload FEC

The OCT modem features strong payload FEC (Section 3.4.5.3).

*Table 3-11 Payload FEC Code Rates (LDPC)*

| PL_RATE | Number of parity bits | Payload Code Rates (LDPC) |
|---|---|---|
| **0** | 0 | N/A |
| **1** | 2304 | 0.8462 |
| **2** | 3456 | 0.7586 |
| **3** | 4992 | 0.6667 |
| **4** | 9216 | 0.5000 |

#### 3.4.6.1.4 Timestamps

In support of external ranging and time transfer calculations, the OCT is required to provide frame timestamps for all frame types 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 populate the timestamp in the header of the outgoing frame. For frames received by the OCT, the OCT is required to populate both time-of-transmit timestamps from the received frame as well as time-of-receipt timestamps measured locally. The OCT is required to provide up to an integer number of frames (TS_RECORD_FRAMES) per second to the host via the OCT-Host ethernet interface. The OCT is required to transmit MGMT frames at frequency of no less than 1 Hz. The timestamps required in the MGMT frame in legacy TWTT shall be the most recent preceding MGMT frame transmission.

**Requirement OCT-066:** The OCT shall insert a timestamp in the header of every modem frame (TX_TS field, TOD_SECONDS) to support two-way time transfer (TWTT) between SV's via OISL, and SV OCT and GEP with OGT.

- The transmit timestamp refers to the time, expressed in the host's clock, at which the start of the frame exits the transmit aperture. The start of the frame is defined as the beginning of the first symbol period of the frame.
- The implementation shall compensate timestamps (as required) for systematic time delays due to propagation paths outside the over-the-air connection between a pair of terminals.
- The TS-applies header bit indicates if the timestamp applies to the current frame (0) or preceding frames (1-7).

**Requirement OCT-067:** The OCT shall collect the transmit timestamp from the header of transmitted modem frames and provide these to the host for TWTT/PNT processing.

**Requirement OCT-068:** The OCT shall collect the transmit timestamp from the header of received modem frames and provide these to the host for TWTT/PNT processing.

**Requirement OCT-069:** The OCT shall collect the ingress time of received modem frames and provide these to the host for TWTT/PNT processing. The received timestamp refers to the time, expressed in the host's clock, at which the start of the frame enters the receive aperture. The start of the frame is defined as the beginning of the first symbol period of the frame.

**Note on Requirement OCT-069:** The means for calibrating path delays and compensating timestamp biases is implementation dependent.

**Requirement OCT-070:** The OCT shall provide the valid TWTT data from the MGMT frame to the host for TWTT/PNT processing from each MGMT frame received.

**Note on Requirement OCT-070:** Valid legacy TWTT timestamps are determined from FIELD_VALID_STRUCTURE of the MGMT payload, shown in Table 3-15. Timestamps with their valid flags set to false are not required to be provided to the host. Valid eTWTT segments are determined by the NUM_SEGMENTS parameter.

**Requirement OCT-071:** The OCT shall provide the collected timestamp information via the network interface.

**Note on Requirement OCT-071:** The format of the timestamp report is implementation specific.

**Requirement OCT-072:** The OCT shall collect 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 on Requirement OCT-072:** Timestamps of IDLE frames other than those required to be recorded and reported may be dropped.

**Requirement OCT-073:** 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-074:** Timestamps shall be accurate to within 3 ns of the host's clock.

#### 3.4.6.2 Fast Control Channel

**Requirement OCT-075:** The OCT modem frame shall provide an embedded fast control channel (FCCH) as described herein.

**Requirement OCT-082:** The OCT shall populate the FCCH messages with valid data and use frame sync status in the LAPC_RSSI_FAST message to determine communication state.

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 (6 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 any 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 3-12 FCCH Logical Channels. If no FCCH data is waiting for transport, the FCCH opcode 111111 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 3-12 FCCH Logical Channels*

| Description | FCCH_Type | FCCH_OPCODE(6 bits) | Message Rate |
|---|---|---|---|
| **Link Quality Reports** | LAPC_BLER_REPORT | 000000 | 1 Hz |
| | LAPC_RSSI_REPORT | 000001 | 1 Hz |
| | LAPC_SYNC_REPORT | 000010 | 1 Hz |
| **Reserved** | RESERVED | 000011 | |
| **OCT Reports** | OCT_CAPABILITIES | 000100 | During Link Acquisition |
| **Link Quality Reports Expansion** | LAPC_RSSI_FAST | 000101 | 100 Hz |
| **Reserved** | RESERVED | 000110-111110 | |
| **Not Preset** | N/A | 111111 | |

The payload for each FCCH message shall be 16-bits. Payloads for each of the FCCH_TYPES are defined in Table 3-13.

*Table 3-13 FCCH Payload*

| FCCH_TYPE | Field | Bits | Description |
|---|---|---|---|
| LAPC_BLER_REPORT<br><br>(Opcode = 000000) | LAPC_RPT_PL_BLER | 16 | Number of payload CRC errors.<br><br>(Trailing 1 sec from 1 PPS) |
| LAPC_RSSI_REPORT<br><br>(Opcode = 000001) | LAPC_RPT_PIF_MEAN | 8 | Received power mean.<br><br>(Average, trailing 1 sec from 1 PPS, step size = -0.25 dBm) |
| | LAPC_RPT_PIF_SDEV | 8 | Received Power standard deviation.<br>(Average, trailing 1 sec from 1 PPS, step size = -0.25 dBm) |
| LAPC_SYNC_REPORT<br><br>(Opcode = 000010) | LAPC_RPT_FS_LOSS | 14 | Number of times frame sync lost<br><br>(Trailing 1 sec from 1 PPS) |
| | LAPC_RPT_FS_STATE | 2 | Frame sync status (at 1 PPS sample time) |
| | | | 00: not locked |
| | | | 01: locked |
| | | | 10-11: reserved |
| OCT_CAPABILITIES<br><br>(Opcode = 000100) | PROTOCOL_VERSION | 16 | 15-12: Major<br><br>11-8: Minor<br><br>7-0: Patch |
| LAPC_RSSI_FAST<br><br>(Opcode = 000101) | LAPC_RPT_RSSI_FAST | 14 | Received Signal Power<br><br>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 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.

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

### 3.4.7 Special Frames

**Requirement OCT-076:** The FRAME_TYPE field of the frame shall signal the type of modem frame as described herein.

This section defines the IDLE and MGMT frame types and their intended usage on the optical interface. The DATA frame type is addressed in Section 3.4.8. Features signaled through the frame header are available in all frame types.

#### 3.4.7.1 IDLE Frames

By design the modem *always* transmits frames with no gap between adjacent frames during nominal operation. 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.

##### 3.4.7.1.1 IDLE 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 TXFN counter.

##### 3.4.7.1.2 IDLE 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 3-1) except with its initial seed equal to the value of the lower 15-bits of the TXFN field in the frame header. If the value of the lower 15-bits 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. If the value of the lower 15-bits of TXFN used to seed the PRBS would null the m-sequence, the seed shall be over-written. 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.

#### 3.4.7.2 MGMT Frames

The MGMT frame type is provided for management frames. These frames are used for inter-OCT communications. MGMT frames shall be correlated to the reference timing signal provided by the host.

##### 3.4.7.2.1 MGMT Header Construction

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

#### 3.4.7.2.2 MGMT 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. Data structures (defined below) are assigned positions in the MGMT frame.

*Table 3-14 MGMT Payload Field Structure*

| Field | Data Type | Field Size (bits) |
|---|---|---|
| **FIELD_VALID** | FIELD_VALID_STRUCTURE | 128 |
| **TWTT_DATA** | TWTT_DATA_STRUCTURE | 376 |
| **EPHEM_PVTR_DATA** | PVTR_DATA_STRUCTURE | 1902 |
| **ETWTT_DATA** | ETWTT_DATA_STRUCTURE | Variable (224 when one segment is used) |
| **Not yet allocated** | Pseudorandom Data | Variable (5786 when one segment is used) |
| **32-bit Payload CRC** | CRC | 32 |
| | **Total** | **8448** |

Further detailed descriptions of the MGMT data field structures are provided in Appendix A.

**Requirement OCT-077**: The EPHEM_PVTR_DATA structure and the associated data fields described in Table 4-4 shall be updated with valid data from the host at a frequency no less than PVTR_REPORT_FREQUENCY, where PVTR_REPORT_FREQUENCY is between 0 and TS_REPORT_FREQUENCY.

The ETWTT_DATA_STRUCTURE, detailed in Table 3-15, contains a configurable number of segments, where each segment describes a linear fit of received timestamps.

*Table 3-15 eTWTT Data Structure*

| Symbol | Data Type | Field Size (bits) | Description |
|---|---|---|---|
| **ESTRUCT_ID** | unsigned integer | 16 | Set to 1 for EWTT_DATA_STRUCTURE. A 0 would indicate no enhanced structures are present. Values of 2 or more correspond to future data structures that have not yet been defined. |
| **LENGTH** | unsigned integer | 16 | Number of bits in this structure. This allows nodes that do not support eTWTT to skip this field. |
| **NUM_SEGMENTS** | unsigned integer | 8 | The number of timestamp segments included. If zero, no ETWTT_SEGMENT data is provided. The size of the frame prevents NUM_SEGMENTS being greater than 32. |
| **ESDATA_1** | ETWTT_SEGMENT | 184 | Structure describing the first |

| | | | |
|---|---|---|---|
| | | | timestamp segment. |
| **ESDATA_2** | ETWTT_SEGMENT | 184 | Structure describing the second timestamp segment. |
| **…** | … | … | … |
| **ESDATA_N** | ETWTT_SEGMENT | 184 | Structure describing the last timestamp segment |

The ESTRUCT_ID field identifies the type of enhanced data structure used, which in this case is an ETWTT_DATA_STRUCTURE. The function of this field is to allow future data structures to be introduced and accommodated in a flexible manner.

The LENGTH field indicates the number of bits consumed by this enhanced structure, including the STRUCT_ID field. This allows terminals that do not recognize or support the STRUCT_ID to skip this structure and move on to the next one. Note that in this document (OCT v3.2.0), only one ESTRUCT_ID is defined so there will be no subsequent structures.

The NUM_SEGMENTS field defines the number of timestamp segments. It also allows for timestamp segments to be declared invalid. If a Host was not able to supply any timestamp segment information, either due to link failure or other faults, it shall set NUM_SEGMENTS to 0. The remote Host would then know not to use this ETWTT_DATA_STRUCTURE.

The ETWTT_SEGMENT structure defines each segment and is documented in Table 3-16.

*Table 3-16 eTWTT Segment Structure*

| Symbol | Data Type | Field Size (bits) | Description |
|---|---|---|---|
| **TX_TOD_SECONDS** | unsigned integer | 6 | TX_TOD_SECONDS and TX_TS represent the timestamp in the remote node's clock of the first frame used in the linear fit. TX_TOD_SECONDS represents the number of seconds in the time-of-day epoch: 0-59. |
| **TX_TS** | unsigned integer | 40 | TX_TOD_SECONDS and TX_TS represent the timestamp in the remote node's clock of the first frame used in the linear fit. TX_TS represents the number of picoseconds of a whole second in time-of-day epoch: 0-999,999,999,999. |
| **TX_INTERVAL** | unsigned integer | 40 | The number of picoseconds in the remote node's clock between the first and last frame used in the linear fit. |
| **PDELAY_START** | signed integer | 44 | The linear fit to the pseudo delay evaluated at the transmit timestamp represented by TX_TOD_SECONDS and TX_TS. Units are ps, so this value can range between ±8.8 sec. |
| **PDELAY_DEV** | signed integer | 32 | Difference between the linear fit to the pseudo delay at the end of the fit interval and the linear fit to the pseudo delay at the start of the fit interval. Dividing this by TX_INTERVAL yields the slope of the fit. Given a maximum fit interval of 1 sec (in $t_1$), the 32-bit size allows for a combined Doppler and oscillator drift of 2147 ppm, with a |

| | | | |
|---|---|---|---|
| | | | resolution of 1 ppb. |
| **RMS_ERR** | unsigned integer | 22 | Root Mean Square (RMS) of residual of linear fit (standard deviation + bias$^2$). N/A if no fitting is performed. Units are 8 ps, so maximum RMS error is 33.6 ns. Errors greater than this should be set to the maximum error. |
| **Total** | | 184 | |

A mathematical description of the linear fit and further discussion of the eTWTT is provided in 4.3 Appendix A.

## 3.4.8 Ethernet Encapsulation

This section describes the structure of the DATA frame type.

### 3.4.8.1 Overview of Ethernet Packet Encapsulation

**Requirement OCT-078:** 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 3-4.

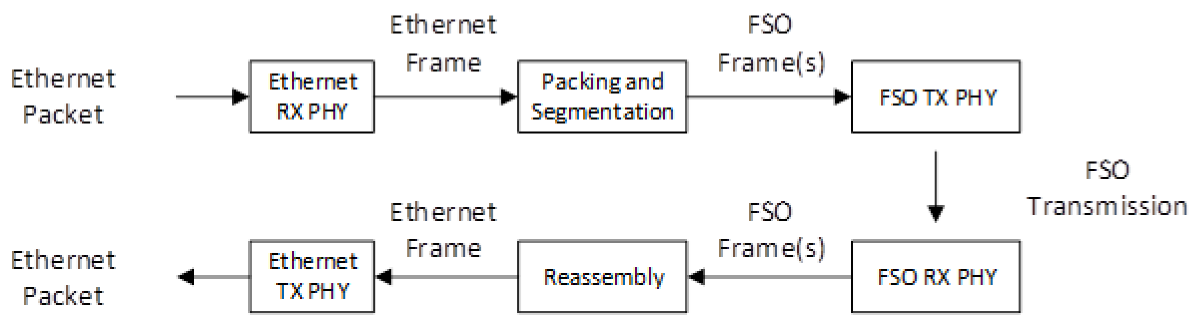


*Figure 3-4 Ethernet Encapsulation*

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.

#### 3.4.8.1.1 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.

#### 3.4.8.1.2 Packing and Segmentation

The *Packing and Segmentation* operation (Figure 3-4) 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

3.4.8.1.3 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 3-5. The bytes must be written into the payload FEC frame in physical byte order. The bytes must be consecutive, per word in Figure 3-5, 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 increment naturally for each 32-bit word in Figure 3-5.

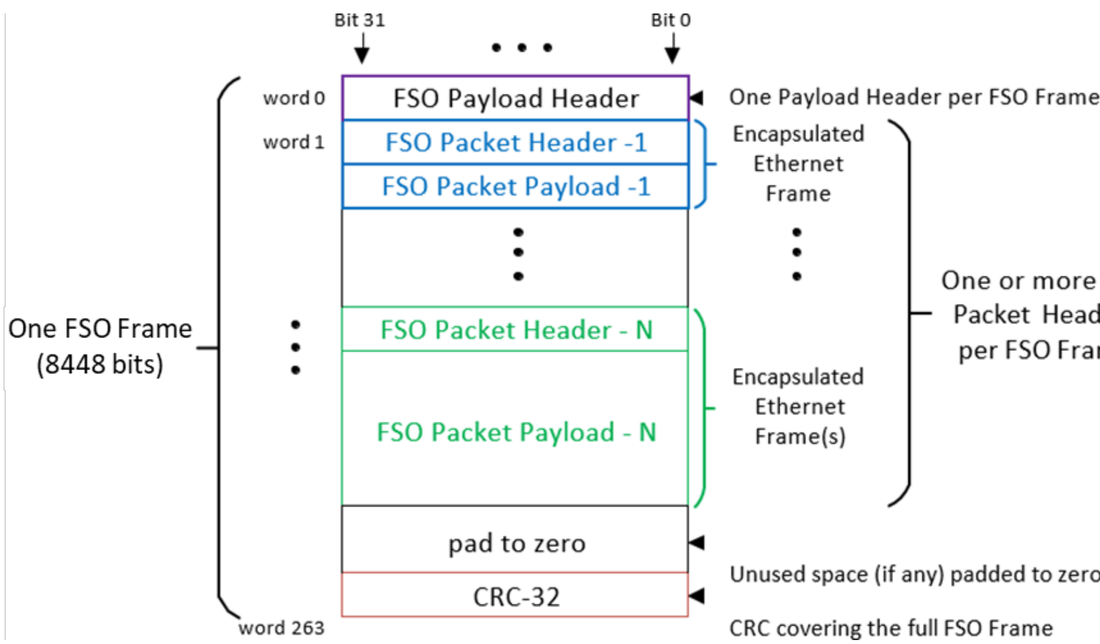


*Figure 3-5 FSO Payload Frame Format*

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 3-5.

Note that the CRC-32 described in Figure 3-5 is the same CRC-32 previously described in and is repeated here for clarity.

3.4.8.1.4 FSO Payload and Packet Headers

**Requirement OCT-079:** Every FSO frame shall start with an FSO payload header.

**Requirement OCT-080:** There shall be exactly one FSO payload header (32 bits) per FSO frame.

**Requirement OCT-081:** The contents of the FSO frame and packet headers shall follow the definition presented in Table 3-17.

*Table 3-17 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 |

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 3-17 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.

The FSO packet header (Table 3-17) 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.

#### 3.4.8.1.5 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 3-5) 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 3-18. The payload header (Table 3-17) 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 3-18 Ethernet Frame Byte Ordering into FSO Logical Frame*

| FSO word number | Contents | 7-0 | 15-8 | 23-16 | 31-24 |
|---|---|---|---|---|---|
| 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 in Section 3.4.8.1.4.

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.

Figure 3-6 provides the implementation convention for data bits into the encoder.

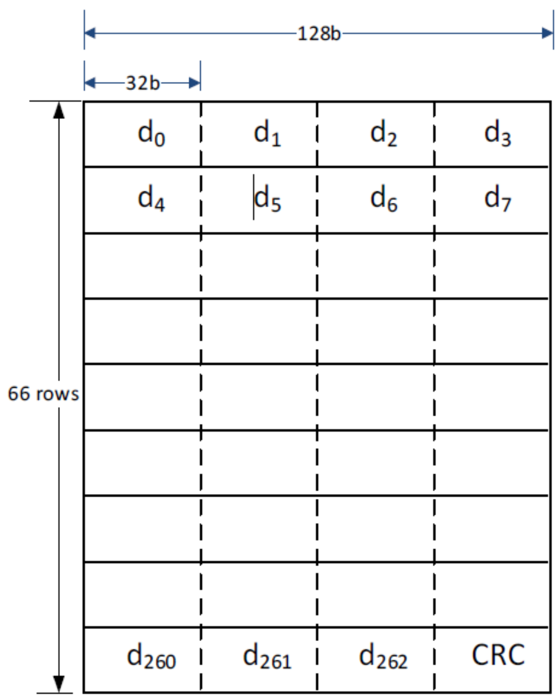


*Figure 3-6 Data Ordering in the LDPC encoder*

- Each 32-bit word in Figure 3-6 corresponds to a row in the Ethernet encapsulation section of this standard. The implemented byte ordering is consistent with the conventions defined for Ethernet encapsulation.
- Data bits are numbered consistently with the 5G-NR family of codes. Here, 32-bit word $d_0$ collects the data bits associated with the first 32 rows of the code's parity check with the

first bit data bit mapped to MSB, the second to MSB-1, down to the 32nd bit mapped to LSB Bits within each 32-bit word are serialized in natural order: $\{b_{31}(MSB), \ldots, b_0(LSB)\}$.

3.4.8.1.6 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 3-4) 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 3-17) is incorrect shall be discarded entirely.
- Any FSO packet header within any FSO frame (Table 3-17) whose magic number is incorrect shall be discarded.
- Any FSO packet header whose length field is inconsistent shall be discarded.

3.4.8.1.7 Transmission Order

The convention for serializing the DATA frame for transmission: data bits enter the scrambler in row major order, with bits within each row serialized as MSB (first) to LSB (last). The process as a function of PL_RATE is illustrated in Figure 3-7.

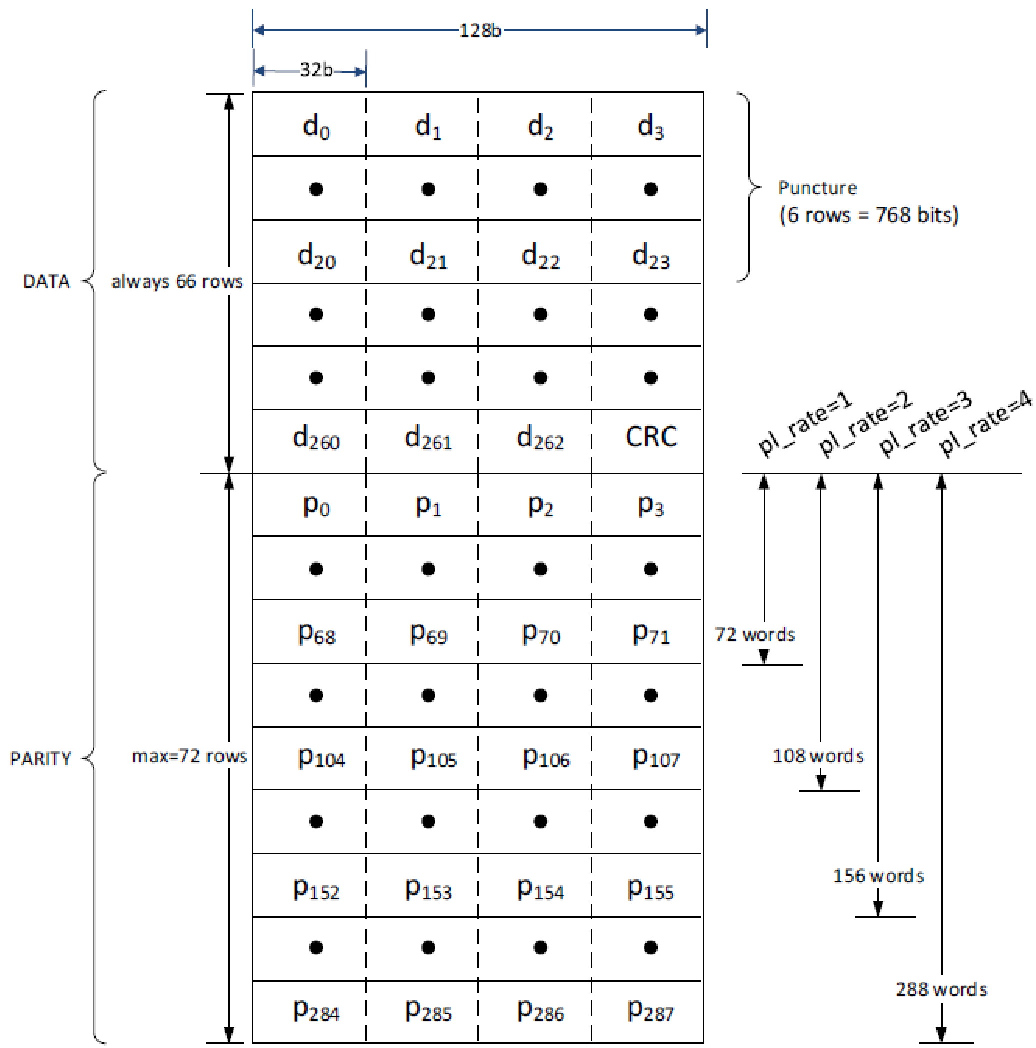


*Figure 3-7 Serialization Order when Payload FEC is Enabled*

### 3.4.9 Effective Data Rate

Table 3-19 summarizes the frame configurations, pertinent metrics, and the resulting data rates for each.

*Table 3-19 Effective Data Rates for Frame Configurations*

| Baud Rate (Mbps) | Line Code | PL RATE | LDPC Code Ratio | Preamble (bits) | Header (bits) | Payload (bits) | Parity (bits) | Total Frame Size (bits) | Optical Signaling Rate (MHz) | Frame Duration (µs) | Max Theoretical Payload Data Rate (Mbps) | FCCH Data Rate (Mbps) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2500 | OOK_NRZ | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 2500 | 3.79 | 2221.28 | 12.67 |
| 2500 | OOK_NRZ | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 2500 | 4.40 | 1911.34 | 10.19 |
| 2500 | OOK_NRZ | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 2500 | 4.86 | 1730.26 | 9.28 |
| 2500 | OOK_NRZ | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 2500 | 5.48 | 1536.21 | 8.30 |
| 2500 | OOK_NRZ | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 2500 | 7.17 | 1174.11 | 6.42 |
| 1250 | Manchester | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 2500 | 7.58 | 1110.64 | 6.33 |
| 1250 | Manchester | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 2500 | 8.81 | 955.67 | 5.10 |
| 1250 | Manchester | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 2500 | 9.73 | 865.13 | 4.64 |
| 1250 | Manchester | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 2500 | 10.96 | 768.11 | 4.15 |
| 1250 | Manchester | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 2500 | 14.34 | 587.05 | 3.21 |
| 1250 | OOK_NRZ | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 1250 | 7.58 | 1110.64 | 6.33 |
| 1250 | OOK_NRZ | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 1250 | 8.81 | 955.67 | 5.10 |
| 1250 | OOK_NRZ | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 1250 | 9.73 | 865.13 | 4.64 |
| 1250 | OOK_NRZ | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 1250 | 10.96 | 768.11 | 4.15 |
| 1250 | OOK_NRZ | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 1250 | 14.34 | 587.05 | 3.21 |
| 625 | Manchester | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 1250 | 15.16 | 555.32 | 3.17 |
| 625 | Manchester | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 1250 | 17.61 | 477.83 | 2.55 |
| 625 | Manchester | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 1250 | 19.46 | 432.57 | 2.32 |
| 625 | Manchester | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 1250 | 21.91 | 384.05 | 2.07 |
| 625 | Manchester | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 1250 | 28.67 | 293.53 | 1.61 |
| 625 | OOK_NRZ | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 625 | 15.16 | 555.32 | 3.17 |
| 625 | OOK_NRZ | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 625 | 17.61 | 477.83 | 2.55 |
| 625 | OOK_NRZ | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 625 | 19.46 | 432.57 | 2.32 |
| 625 | OOK_NRZ | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 625 | 21.91 | 384.05 | 2.07 |

| Baud Rate (Mbps) | Line Code | PL RATE | LDPC Code Ratio | Preamble (bits) | Header (bits) | Payload (bits) | Parity (bits) | Total Frame Size (bits) | Optical Signaling Rate (MHz) | Frame Duration (µs) | Max Theoretical Payload Data Rate (Mbps) | FCCH Data Rate (Mbps) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 625 | OOK_NRZ | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 625 | 28.67 | 293.53 | 1.61 |
| 313 | Manchester | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 626 | 30.31 | 277.66 | 1.59 |
| 313 | Manchester | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 626 | 35.23 | 238.92 | 1.28 |
| 313 | Manchester | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 626 | 38.91 | 216.28 | 1.16 |
| 313 | Manchester | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 626 | 43.83 | 192.03 | 1.04 |
| 313 | Manchester | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 626 | 57.34 | 146.76 | 0.80 |
| 313 | OOK_NRZ | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 313 | 30.31 | 277.66 | 1.59 |
| 313 | OOK_NRZ | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 313 | 35.23 | 238.92 | 1.28 |
| 313 | OOK_NRZ | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 313 | 38.91 | 216.28 | 1.16 |
| 313 | OOK_NRZ | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 313 | 43.83 | 192.03 | 1.04 |
| 313 | OOK_NRZ | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 313 | 57.34 | 146.76 | 0.80 |
| 156 | Manchester | 0 | 0.00 | 64 | 960 | 8448 | 0 | 9472 | 312 | 60.62 | 138.83 | 0.79 |
| 156 | Manchester | 1 | 0.85 | 64 | 960 | 8448 | 2304 | 11008 | 312 | 70.45 | 119.46 | 0.64 |
| 156 | Manchester | 2 | 0.76 | 64 | 960 | 8448 | 3456 | 12160 | 312 | 77.82 | 108.14 | 0.58 |
| 156 | Manchester | 3 | 0.67 | 64 | 960 | 8448 | 4992 | 13696 | 312 | 87.65 | 96.01 | 0.52 |
| 156 | Manchester | 4 | 0.50 | 64 | 960 | 8448 | 9216 | 17920 | 312 | 114.69 | 73.38 | 0.40 |

### 3.4.10 LDPC Code Rates

The OCT modem implementation supports the four payload FEC code rates listed in Table 3-20.

*Table 3-20 Payload FEC Code Rates*

| PL Rate | Total Size (Bits) | Z | mb | Parity Check (Bits) | K mod | Actual Code-Rate Ratio | K, Information Block size (Bits) |
|---|---|---|---|---|---|---|---|
| **1** | 9984 | 384 | 6 | 2304 | 7680 | 0.8462 | 8448 |
| **2** | 11136 | 384 | 9 | 3456 | 7680 | 0.7586 | 8448 |
| **3** | 12672 | 384 | 13 | 4992 | 7680 | 0.6667 | 8448 |
| **4** | 16896 | 384 | 24 | 9216 | 7680 | 0.5000 | 8448 |

# 4 Appendix A

The legacy timestamp structures below support TWTT for OCTs compliant up to version 3.2.0 of the OCT standard. These fields may be subject to removal or recycling in future versions but are present here for backwards compatibility for OCTs compliant to version 4.0.0 onwards.

## 4.1 Legacy TWTT

The FIELD_VALID_STRUCTURE of the MGMT payload is shown in Table 4-1.

*Table 4-1 FIELD_VALID_STRUCTURE*

| Field | Field Size (bits) |
|---|---|
| **TWTT_VALID_1** | 1 |
| **TWTT_VALID_2** | 1 |
| **TWTT_VALID_3** | 1 |
| **TWTT_VALID_4** | 1 |
| **EPHEM_PVTR_VALID** | 1 |
| **RESERVED** | 123 |

The TWTT_DATA_STRUCTURE of the MGMT payload is shown in Table 4-2.

*Table 4-2 TWTT_DATA_STRUCTURE*

| Symbol | Field Valid Flag | Data Type | Field Size (bits) | Description |
|---|---|---|---|---|
| **$t_1(n)$** | TWTT_VALID_1 | FRAME_TIME_STAMP_STRUCTURE | 94 | The time frame *n* from remote to local exits the remote transmit aperture, as measured by the remote aperture. |
| **$t_2(m)$** | TWTT_VALID_2 | FRAME_TIME_STAMP_STRUCTURE | 94 | The time frame *m* from local to remote exits the local transmit aperture, as measured by the local aperture.. |
| **$t_3(n)$** | TWTT_VALID_3 | FRAME_TIME_STAMP_STRUCTURE | 94 | The time frame *n* from remote to local enters the local receive aperture, as measured by the local aperture. |
| **$t_4(m)$** | TWTT_VALID_4 | FRAME_TIME_STAMP_STRUCTURE | 94 | The time frame m from local to remote enters the |

| | | | | |
|---|---|---|---|---|
| | | | | remote receive aperture, as measured by the remote aperture. |
| | | **Total** | **376** | |

Note: Timestamps not available to the OCT at the time of MGMT frame generation will have their respective TWTT_VALID_* flag set to 0 (zero) and those timestamps will be ignored for purposes of TWTT.

The detail of the FRAME_TIME_STAMP_STRUCTURE is shown in the Table 4-3.

*Table 4-3 FRAME_TIME_STAMP_STRUCTURE*

| Field | Field Size (bits) | Description |
|---|---|---|
| PVTR_TS | 40 | TX timestamp (frame egress), number of whole picoseconds of whole second in time-of-day epoch: 0-999,999,999,999 |
| PVTR-tod | 6 | The number of seconds in time-of-day epoch: 0-59 |
| Total | 46 | |

## 4.2 PVTR Data

The PVTR_DATA_STRUCTURE of the MGMT payload is shown in the Table 4-4. Filling this structure, and it's associated sub-structures, with valid data is optional for systems compliant to OCT Standard 3.1.0 and prior versions. For OCT Standard 3.2.0 compliant systems, the SC_PVTR_TIMESTAMP and SC_POSITION_VELOCITY sub-structures shall be filled with valid data.

*Table 4-4 PVTR_DATA_STRUCTURE*

| Field | Data Type | Field Size (bits) |
|---|---|---|
| **SC_PVTR_TIMESTAMP** | SC_PVTR_TIMESTAMP_TYPE | 46 |
| **SC_POSITION_VELOCITY** | SC_POSITION_VELOCITY_VECTOR_STRUCTURE | 384 |
| **SC_POSITION_VELOCITY_COVAR** | SC_POSITION_VELOCITY_COVARIANCE_DATA_STRUCTURE | 384 |
| **SC_ATTITUDE_QUATERNION** | QUATERNION_STRUCTURE | 256 |
| **SC_TO_OCT_TRANSLATION** | VECTOR_STRUCT | 192 |
| **SC_TO_OCT_ROTATION_QUATERNION** | QUATERNION_STRUCTURE | 256 |
| **OCT_LOS_UNIT_VECTOR** | VECTOR_STRUCT | 192 |
| **OCT_LEVER_ARM_VECTOR** | VECTOR_STRUCT | 192 |
| | **Total** | **1902** |

When data is updated inside the PVTR_DATA_STRUCTURE fields, the timestamps inside the SC_PVTR_TIMESTAMP_TYPE shall be updated to reflect the GPS epoch time in milliseconds at which the data inside the PVTR_DATA_STRUCTURE was last valid. The PVTR timestamps are not updated if PVTR_DATA_STRUCTURE is not updated. SC_PVTR_TIMESTAMP_TYPE fields are shown in Table 4-5.

*Table 4-5 SC_PVTR_TIMESTAMP_TYPE*

| Field | Field Size (bits) | Description |
|---|---|---|
| **PVTR_TS** | 40 | GPS Epoch time in milliseconds when PVTR data was last valid. |
| **PVTR_TOD** | 6 | The number of seconds in time-of-day epoch: 0-59 |
| **Total** | 46 | |

The detail of the SC_POSITION_VELOCITY_VECTOR_STRUCTURE is shown in Table 4-6. All values are single precision floats (32 bits), left padded with 32 bits of zeros and reference coordinates in an earth-centered inertial reference frame using the J2000 model.

*Table 4-6 SC_POSITION_VELOCITY_VECTOR_STRUCTURE*

| Field | Field Size (bits) | Units |
|---|---|---|
| **X** | 64 | m |
| **Y** | 64 | m |
| **Z** | 64 | m |
| $\dot{X}$ | 64 | m/s |
| $\dot{Y}$ | 64 | m/s |
| $\dot{Z}$ | 64 | m/s |
| **Total** | **384** | |

The detail of the SC_POSITION_VELOCITY_COVARIANCE_DATA_STRUCTURE is shown in Table 4-7.

*Table 4-7 SC_POSITION_VELOCITY_COVARIANCE_DATA_STRUCTURE*

| Field | Field Size (bits) |
|---|---|
| **COV_XX** | 64 |
| **COV_XY** | 64 |
| **COV_XZ** | 64 |
| **COV_YY** | 64 |
| **COV_YZ** | 64 |
| **COV_ZZ** | 64 |
| **Total** | **384** |

The detail of the QUATERNION_STRUCTURE is shown in Table 4-8.

Table 4-8 QUATERNION_STRUCTURE

| Field | Field Size (bits) |
|---|---|
| **a** | 64 |
| **b** | 64 |
| **c** | 64 |
| **d** | 64 |
| **Total** | **256** |

The detail of the VECTOR_STRUCT is shown in Table 4-9.

Table 4-9 VECTOR_STRUCT

| Field | Field Size (bits) |
|---|---|
| **x** | 64 |
| **y** | 64 |
| **z** | 64 |
| **Total** | **192** |

## 4.3 Enhanced TWTT

With respect to the "local" terminal, we can define the following four categories of timestamps, illustrated in Figure 4-1:

1. $t_1(n)$: the time frame $n$ from remote to local exits the remote transmit aperture, as measured by the remote OCT using the remote host's clock.
2. $t_3(n)$: the time frame $n$ from remote to local enters the local receive aperture, as measured by the local OCT using the local host's clock.
3. $t_2(m)$: the time frame $m$ from local to remote exits the local transmit aperture, as measured by the local OCT using the local host's clock.
4. $t_4(m)$: the time frame $m$ from local to remote enters the remote receive aperture, as measured by the remote OCT using the remote host's clock.

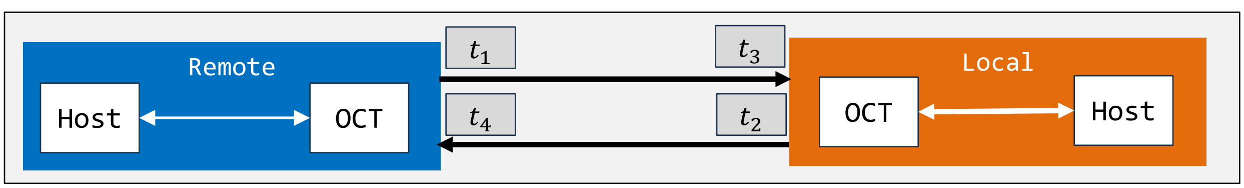


Figure 4-1: Timestamp Definitions

Remember these are defined with respect to the local terminal. If we change our focus and label the other terminal as "local," the timestamp definitions will flip, with $t_1$ switching meanings with $t_2$ and $t_3$ switching meanings with $t_4$. Figure 4-2 illustrates the timestamp information exchange between two nodes using eTWTT.

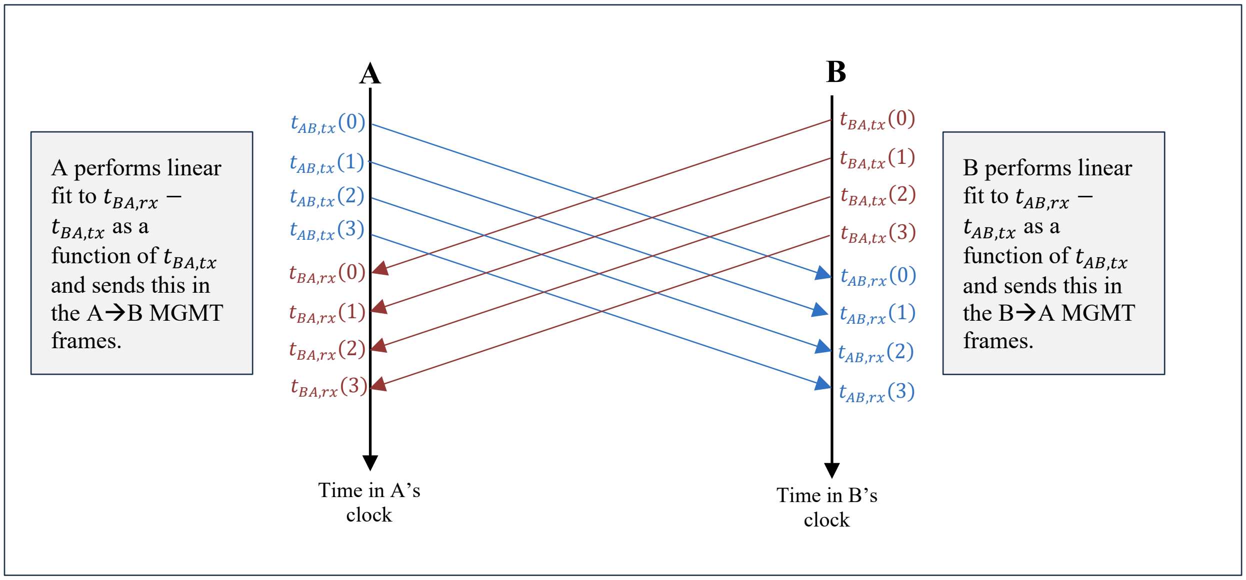


*Figure 4-2: A Broader View of Timestamp Exchange*

For frames from $n = n_{\text{start}}$ to $n_{\text{stop}}$, the local OCT knows $t_1(n)$ and $t_3(n)$. The pseudo delay is defined as $t_3(n) - t_1(n)$; it is the difference between the arrival time in the receiver's clock and the transmit time in the transmitter's clock. The local receiver approximates the pseudo delay as an affine function of the transmit timestamps $t_1(n)$. The $\alpha$ and $\beta$ terms are the slope and y-intercept, respectively, of a linear fit to the pseudo delay.

$$f_{13}\big(t_1(n)\big) = \alpha t_1(n) + \beta \approx t_3(n) - t_1(n) \qquad \text{(Eq. 6)}$$

If we instead desired to fit the receive time $t_3$ to the transmit time $t_1$, we would have:

$$f_3\big(t_1(n)\big) = (\alpha + 1)t_1(n) + \beta \approx t_3(n) \qquad \text{(Eq. 7)}$$

We can see from the above that this is the same problem and will have the same solution, except the slope is $\alpha + 1$ rather than $\alpha$. For the sake of efficiency, we define the linear fit to be in terms of the pseudo delay, recognizing that we can easily compute the receive time by adding the pseudo delay to the transmit time. The best linear fit minimizes the minimum mean squared error.

$$MSE = \frac{1}{N_s}\sum_{n=n_{\text{start}}}^{n_{\text{stop}}} |(\alpha + 1)t_1(n) + \beta - t_3(n)|^2 \qquad \text{(Eq. 8)}$$

Where $N_s = n_{\text{stop}} - n_{\text{start}} + 1$.

Figure 4-3 illustrates the linear fit to pseudo delay in the context of eTWTT.

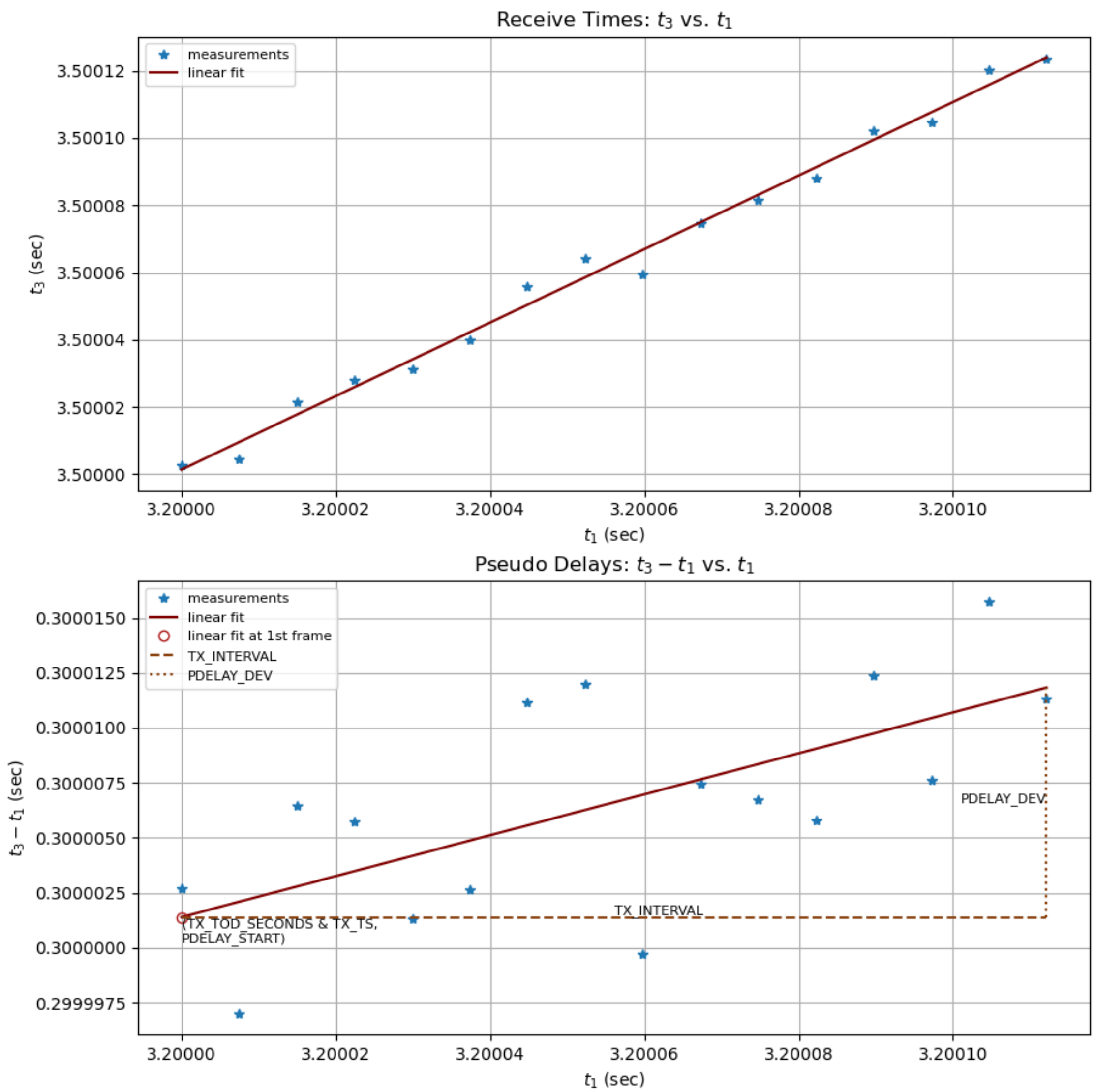


*Figure 4-3: Linear Fit to Pseudo Delays in eTWTT*

This document does not specify the linear fit implementation, which the vendor is free to perform however it sees fit. The following equations shown provides a simple reference pseudo-code of a recursive implementation as an example. The solution for the least-squares linear fit on the timestamps for eTWTT is given by the following:

$$\alpha = \frac{\rho}{\sigma_1^2} \quad , \ \beta = \bar{t}_3 - (\alpha+1)\cdot\bar{t}_1 \ , \ MSE = \sigma_{13}^2 - \frac{\rho^2}{\sigma_1^2} \qquad \text{(Eq. 9)}$$

In these equations, $\overline{t_3}$ and $\overline{t_1}$ are the means of $t_3(n)$ and $t_1(n)$:

$$\overline{t_3} = \frac{1}{N_s}\sum_{n=n_{\text{start}}}^{n_{\text{stop}}} t_3(n)\ , \quad \overline{t_1} = \frac{1}{N_s}\sum_{n=n_{\text{start}}}^{n_{\text{stop}}} t_1(n)$$

Define $\overline{t_3^2}$ and $\overline{t_1^2}$ to be the average sum of the squares of $t_3(n)$ and $t_1(n)$.

$$\overline{t_3^2} = \frac{1}{N_s}\sum_{n=n_{\text{start}}}^{n_{\text{stop}}} \big(t_3(n)\big)^2\ , \quad \overline{t_1^2} = \frac{1}{N_s}\sum_{n=n_{\text{start}}}^{n_{\text{stop}}} \big(t_1(n)\big)^2$$

Define $\overline{t_{13}}$ to be the average product of $t_1(n)$ and $t_3(n)$:

$$\overline{t_{13}} = \frac{1}{N_s}\sum_{n=n_{\text{start}}}^{n_{\text{stop}}} t_1(n)t_3(n)$$

Define also $\sigma_1^2$ and $\sigma_{13}^2$ as follows. Note that $\overline{t_1^2}$ is the mean of the squares of $t_1$, whereas $\overline{t_1}^2$ is the square of the mean of $t_1$, and likewise for $\overline{t_3^2}$ and $\overline{t_3}^2$.

$$\sigma_1^2 = \overline{t_1^2} - \overline{t_1}^2, \qquad \sigma_{13}^2 = \overline{t_3^2} + \overline{t_1^2} - 2\overline{t_{13}} - (\overline{t_3} - \overline{t_1})^2$$

Finally, $\rho$ is computed as follows:

$$\rho = \frac{1}{N_s}\sum_{n=n_{start}}^{n_{stop}} \big((t_3(n) - \overline{t_3}) - (t_1(n) - \overline{t_1})\big)(t_1(n) - \overline{t_1})$$

$$\rho = \overline{t_1}^2 - \overline{t_1^2} + \overline{t_{13}} - \overline{t_3}\,\overline{t_1}$$

These computations can be performed recursively as new timestamps are available. There is no need to store past timestamp data. Each iteration of the for loop can be executed after the reception of a frame. The initial and final computations are performed just once per MGMT frame.

Timestamps variables at initialization:

$t_{3,sum} = 0$
$t_{1,sum} = 0$
$t_{13,sum} = 0$
$t_{3,sum}^2 = 0$
$t_{1,sum}^2 = 0$

The following two loops show how the timestamps variables and their associated averages may be recursively defined:

For $n = n_{\text{start}}$ to $n_{\text{stop}}$:

$t_{3,sum} = t_{3,sum} + t_3(n)$
$t_{1,sum} = t_{1,sum} + t_1(n)$

$$t_{13,sum} = t_{13,sum} + t_1(n)t_3(n)$$
$$t_{3,sum}^2 = t_{3,sum}^2 + \left(t_3(n)\right)^2$$
$$t_{1,sum}^2 = t_{1,sum}^2 + \left(t_1(n)\right)^2$$

End
For

$$\overline{t_3} = \frac{t_{3,sum}}{N_s}$$
$$\overline{t_1} = \frac{t_{1,sum}}{N_s}$$
$$\overline{t_{13}} = \frac{t_{13,sum}}{N_s}$$
$$\overline{t_3^2} = \frac{t_{3,sum}^2}{N_s}$$
$$\overline{t_1^2} = \frac{t_{1,sum}^2}{N_s}$$
$$\sigma_1^2 = \overline{t_1^2} - \overline{t_1}^2$$
$$\sigma_{13}^2 = \overline{t_3^2} + \overline{t_1^2} - 2\overline{t_{13}} - (\overline{t_3} - \overline{t_1})^2$$
$$\rho = \overline{t_1}^2 - \overline{t_1^2} + \overline{t_{13}} - \overline{t_3}\,\overline{t_1}$$
$$\alpha = \frac{\rho}{\sigma_1^2}$$
$$\beta = \bar{\mathrm{t}}_3 - (\alpha + 1) \cdot \bar{\mathrm{t}}_1$$
$$MSE = \sigma_{13}^2 - \frac{\rho^2}{\sigma_1^2}$$

End

The parameters shared in the MGMT frame are as follows.

*Table 4-10 MGMT Parameters*

| Field | Symbol |
|---|---|
| **TX_TOD_SECONDS** | $t_1(n_{start})$ |
| **TX_TS** | $t_1(n_{start})$ |
| **TX_INTERVAL** | $t_1(n_{stop}) - t_1(n_{start})$ |
| **PDELAY_START** | $f_3(t_1(n_{start})) = \beta + \alpha t_1(n_{start})$ |
| **PDELAY_DEV** | $\alpha\left(t_1(n_{stop}) - t_1(n_{start})\right)$ |
| **RMS_ERR** | $\sqrt{MSE}$ |

# 5 References

The following publications contain provisions that, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below.


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