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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Access networks – Optical line systems for local and access networks

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Higher speed passive optical networks – Common transmission convergence layer specification

Recommendation ITU-T G.9804.2

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Recommendation ITU-T G.9804.2

Higher speed passive optical networks – Common transmission convergence layer specification

Summary

Recommendation ITU-T G.9804.2 specifies the common transmission convergence (ComTC) layer of Higher Speed passive optical network (HSP) systems providing optical access for residential, business, mobile backhaul and other applications. This specification defines operation of HSP systems in a manner agnostic of transmission rates, number of operating wavelength channels, and signal modulation. It is intended to be applicable to systems implementing a subset of the specified range of features.

An HSP system enables protocol flexibility to support higher performance physical media dependent (PMD) interfaces without impacting the definition of the associated ComTC layer. An HSP system does not require an implementation to support all possible ComTC features. The intent is to provide the definition and behaviour of a ComTC layer independent of line rate, number of wavelength channels, and signal modulation. Actual systems would be based on features chosen for implementation and available supporting technology.

The ComTC layer is the protocol layer of the HSP system that is positioned between the PMD layer and service clients. It builds on the ITU-T G.987.3, ITU-T G.9807.1, and ITU-T G.989.3 Recommendations, with modifications to support specific features, primarily rate flexibility, single and multiple wavelength operation, and signal modulation.

This Recommendation forms an integral part of the ITU-T G.hsp series of Recommendations (ITU-T G.9804.1 and applicable PMD Recommendations) that, together with the ONU management and control interface (OMCI), Recommendation ITU-T G.988, specifies a set of access transmission systems.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G.9804.2	2021-09-06	15	11.1002/1000/14645

Keywords

ComTC, HSP, TDM, TWDM.

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1 Scope

This Recommendation specifies the common transmission convergence (ComTC) layer of higher speed passive optical network (HSP) systems, providing optical access for residential, business, mobile backhaul, and other applications. HSP systems operate at rates specified in related PMD recommendations. This Recommendation supports both time division multiplexing (TDM), and time and wavelength division multiplexing (TWDM) modes of operation. As a general rule, TDM operation is considered a single wavelength channel pair case of TWDM operation. This Recommendation uses line rate parameterization to generalize the TC functions to enable a line rate agnostic TC specification for all HSP systems.

This Recommendation specifies:

– a layered structure containing three sublayers;
– functionality of the ComTC service adaptation sublayer, including the use of 10-Gigabit passive optical network (XG-PON) encapsulation method (XGEM), XGEM frame delineation, and service data unit (SDU) fragmentation;
– functionality of the ComTC framing sublayer with the specification of the downstream frame and upstream burst formats;
– functionality of the ComTC physical interface (PHY) adaptation sublayer, including synchronization, forward error correction, scrambling, and downstream interleaving;
– PON embedded management functionality, including control of the upstream time-division multiple access and dynamic bandwidth assignment mechanisms;
– the physical layer operation, administration, and management (PLOAM) messaging channel;
– the optical network unit (ONU) activation cycle state machine, covering activation, and wavelength channel handover;
– timing aspects of PON point-to-multipoint operation and time-of-day communication;
– performance monitoring, supervision, and defects;
– security including cryptographic mechanisms for authentication, integrity verification, channel isolation, and data protection along with the associated key exchange protocols;
– signalling mechanisms and protocols to support ONU power management;
– wavelength channel management;
– system protection;
– alien device and rogue ONU behaviour mitigation.

1.1 Line rate parameterization and PMD specification applicability

This Recommendation is compatible with a wide class of PMD layer specifications describing single channel (TDM) and multiple channel (TWDM) PON systems that operate at the nominal downstream line rate in excess of 9.95328 Gbit/s and maintain the physical layer frame size of 125 μs. Any linkage to the actual line rates specified in such PMD specifications is confined to this subclause. With the line rate parameterization introduced below, the present specification is fully applicable to the HSP PON systems compliant with any PMD layer specification listed in Table 1-1. It is expected that minimal or no modifications should be necessary when expanded to support future systems.

Notation ρ_0 denotes the *fundamental rate* of the system, from which any actual line rate in either downstream or upstream direction is obtained as an integer multiple.

Notation ϕ_0 denotes a multiplicative integer *line rate factor* that is used to obtain the full nominal line rate in the system, which is necessarily the nominal downstream line rate. The line rate factors used to obtain the other nominal line rates in the system are denoted ϕ_1, ϕ_2, etc. Whenever used without a subscript, line rate factor ϕ applies to the operational nominal line rate of a device. Thus, the nominal line rate is $\rho_0\phi$.

Table 1-1 lists the HSP PMD layer Recommendations with which the present Common TC Layer Recommendation is compatible, along with the respective parameter values. The future PMD Recommendations may provide additional rows to this table.

Table 1-1 – Line rate parameterization

PMD layer	Fundamental line rate, ρ_0, Gbit/s	Line rate factor, ϕ_0 (Full nominal line rate, $\rho_0\phi_0$, Gbit/s)	Line rate factor ϕ_1 (Upstream line rate 1, $\rho_0\phi_1$, Gbit/s)	Line rate factor ϕ_2 (Upstream line rate 2, $\rho_0\phi_2$, Gbit/s)
50G-TDM (ITU-T G.9804.3)	12.4416	4 (49.7664)	2 (24.8832)	1 (12.4416)
50G-TWDM (ITU-T G.9804.4)	12.4416	4 (49.7664)	2 (24.8832)	1 (12.4416)

1.2 Compliance

The present Recommendation specifies general principles, methods, formats, and procedures applicable across multiple nominal line rates and to PON systems with variable number of wavelength channels. A PON system compliant with the present Recommendation may be restricted to a specific set of line rates and to a TDM system as a single wavelength channel pair case ofmultiple wavelength channel pair system, e.g., TWDM. Therefore, a compliant system has a restricted rate or set of rates and a chosen operating mode. It can be envisioned that a system could support a range of specified operating rates, operating in TDM or TWDM mode, depending on the deployed configuration. In either mode, a compliant system must conform to all the normative behaviours consistent with a selected rate or mode as described herein.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.987.3] Recommendation ITU-T G.987.3 (2014), *10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification.*

[ITU-T G.988] Recommendation ITU-T G.988 (2017), *ONU management and control interface (OMCI) specification.*

[ITU-T G.989.1]	Recommendation ITU-T G.989.1 (2015), *40-Gigabit-capable passive optical networks (NG-PON2): General requirements.*
[ITU-T G.989.2]	Recommendation ITU-T G.989.2 (2020), *40-Gigabit-capable passive optical networks (NG PON2): Physical media dependent (PMD) layer specification.*
[ITU-T G.989.3]	Recommendation ITU-T G.989.3 (2020), *40-Gigabit-capable passive optical networks (NG PON2): Transmission Convergence (TC) layer specification*.
[ITU-T G.9804.1]	Recommendation ITU-T G.9804.1 (2019), *Higher speed passive optical networks – Requirements*.
[ITU-T G.9807.1]	Recommendation ITU-T G.9807.1 (2016), *10-Gigabit-capable symmetric passive optical network (XGS-PON).*
[ITU-T I.432.1]	Recommendation ITU-T I.432.1 (1999), *B-ISDN user-network interface – Physical layer specification: General characteristics.*
[ISO/IEC 18033-3]	ISO/IEC 18033-3:2010, *Information technology – Security techniques – Encryption algorithms – Part 3: Block ciphers*.
[NIST FIPS-197]	NIST Federal Information Processing Standards Publication 197 (2001), *Advanced Encryption Standard (AES).*
[NIST SP800-38A]	NIST Special Publication 800-38A (2001), *Recommendation for Block Cipher Modes of Operation – Methods and Techniques.*
[NIST SP800-38B]	NIST Special Publication 800-38B (2005), *Recommendation for Block Cipher Modes of Operation: The CMAC Mode for Authentication.*

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

See clause 3 of [ITU-T G.9804.1].

3.2 Terms defined in this Recommendation

This Recommendation defines the following term:

3.2.1 time quantum: A line-rate-invariant unit of time which is equal to ($128\times\phi$) bit periods at the line rate of $\rho_0\phi$. Time quantum is represented by Q_0 in this Recommendation. The approximate value of Q_0 is 10.288 ns.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

See clause 4 of [ITU-T G.9804.1].

5 Conventions

See clause 5 of [ITU-T G.9804.1].

6 ComTC layer overview

The ComTC layer specification supports a higher speed passive optical network (HSP) system containing one or more wavelength channel pairs. An HSP system containing one wavelength channel pair is said to operate in a TDM mode; an HSP system containing multiple wavelength channel pairs is said to operate in the TWDM mode.

As this Recommendation serves as a rate agnostic specification, the rate parameterization described in clause 1.1 is used.

This clause overviews the ComTC layer. Herein the optical line terminal (OLT) channel termination (OLT CT) refers to the logical function residing at the OLT network element that terminates one single wavelength channel pair, regardless of whether TDM or TWDM operation mode is used.

The remainder of clause 6 is structured as follows. Clause 6.1 describes supported line rate combinations; clause 6.2 introduces the sublayer structure of the ComTC layer and reviews the transformation of a service data unit (SDU) as it crosses the sublayers; clause 6.3 discusses the basic functionality of the three sublayers of the ComTC layer; clause 6.4 provides an overview of the three management channels in an HSP system; clause 6.5 discusses the principles and identifiers; finally, clause 6.6 reviews the basics of the upstream media access control.

6.1 Supported nominal line rates

This Recommendation is applicable to the OLT CTs and ONUs that support downstream/upstream nominal line rate defined in the physical media dependent (PMD) Recommendations of HSP systems referenced in Table 1-1, between any two consecutive events involving CT reconfiguration or replacement. Line rate parameterization to generalize the supported nominal line rates in the applicable PMD Recommendations is described in clause 1.1[1].

An OLT CT or ONU shall be capable to support at least one combination of downstream/upstream nominal line rates defined in the associated PMD Recommendation listed in Table 1-1.

An OLT CT may support multiple nominal line rate combinations with the associated multi-rate upstream channel, capable of accommodating ONUs supporting different nominal line rate combinations within the same PHY frame.

An ONU may support one or multiple nominal line rate combination defined in the corresponding clauses of associated PMD Recommendations, within one ONU's activation cycle.

It is applicable to ONUs satisfying the following condition:

– an ONU supporting multiple upstream nominal line rates within an activation cycle, whereby a change of upstream line rate is either associated with tuning between wavelength channels or performed within a single multi-rate upstream wavelength channel.

The mechanism for dynamic configuration of the upstream nominal line rate is for future study.

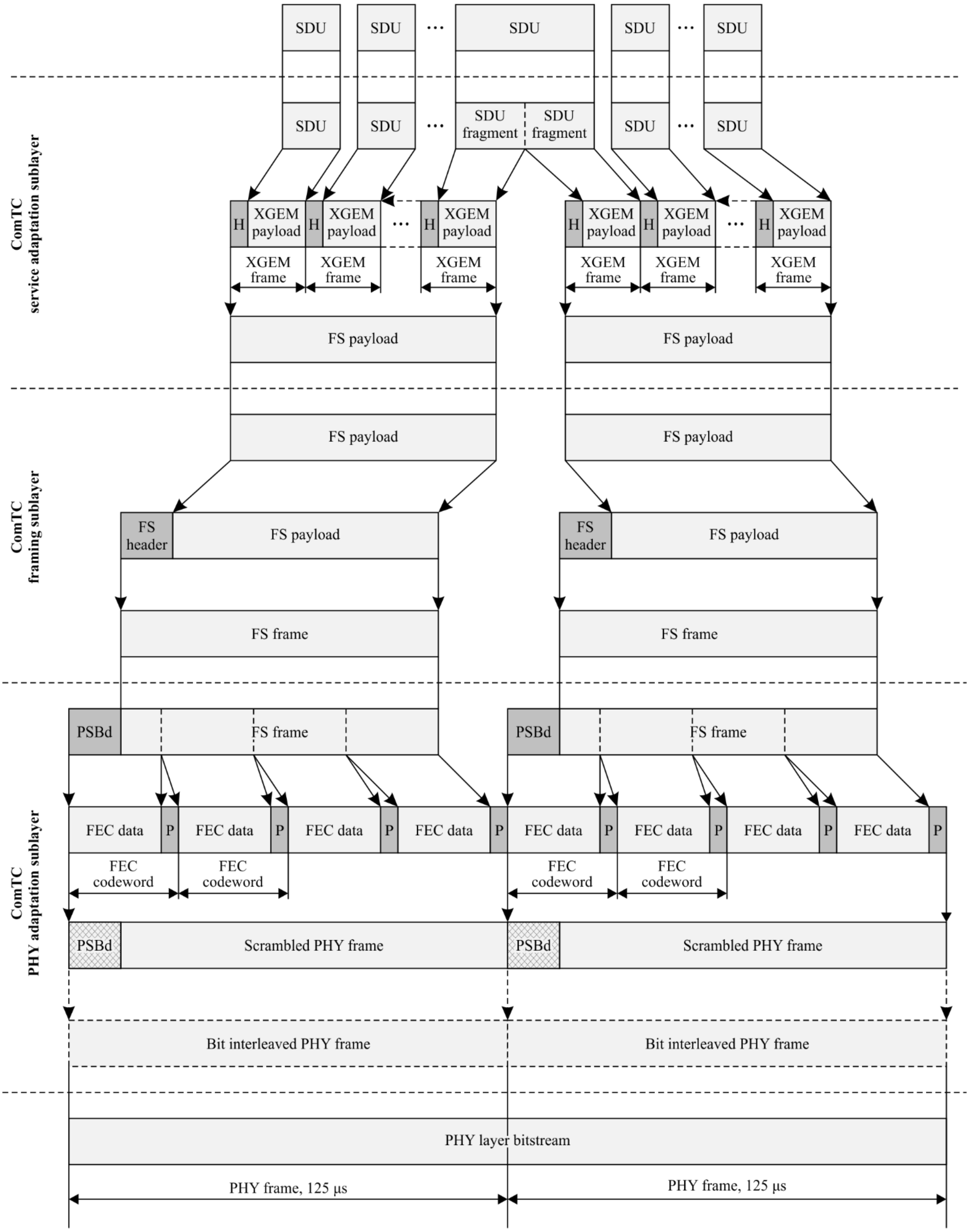
6.2 ComTC layer structure

This Recommendation specifies the formats and procedures of mapping between the upper layer SDUs and a bitstream suitable for modulating the optical carrier.

The ComTC layer is composed of three sublayers: the ComTC service adaptation sublayer, the ComTC framing sublayer, and the ComTC PHY adaptation sublayer. The ComTC layer is bidirectional between the OLT and ONUs of an HSP system. In the downstream direction, the interface between the ComTC layer and the PMD layer is represented by a continuous bitstream

[1] Global parameters of this Recommendation are specified in clause 1.1. Other parameters are with local scope.

at the nominal line rate, which is partitioned into 125 μs frames. In the upstream direction, the interface between the ComTC layer and the PMD layer is represented by a sequence of precisely timed bursts. The key transformation stages involved in the mapping between the upper layer SDUs and the PHY bitstream for the downstream and upstream directions are shown in Figure 6-1 and Figure 6-2, respectively. Note that Figure 6-1 shows 4 FEC codewords as an example. The actual number of downstream FEC codewords in a PHY frame is specified in clause 10.3.1. The actual number of upstream FEC codewords depends on the size of the burst (see clause 10.3.2). Figure 6-2 shows 3 FEC codewords as an example.



H – XGEM frame header
P – FEC parity
NOTE – Interleaving of a PHY frame is an option

Figure 6-1 – Downstream SDU mapping into PHY frames

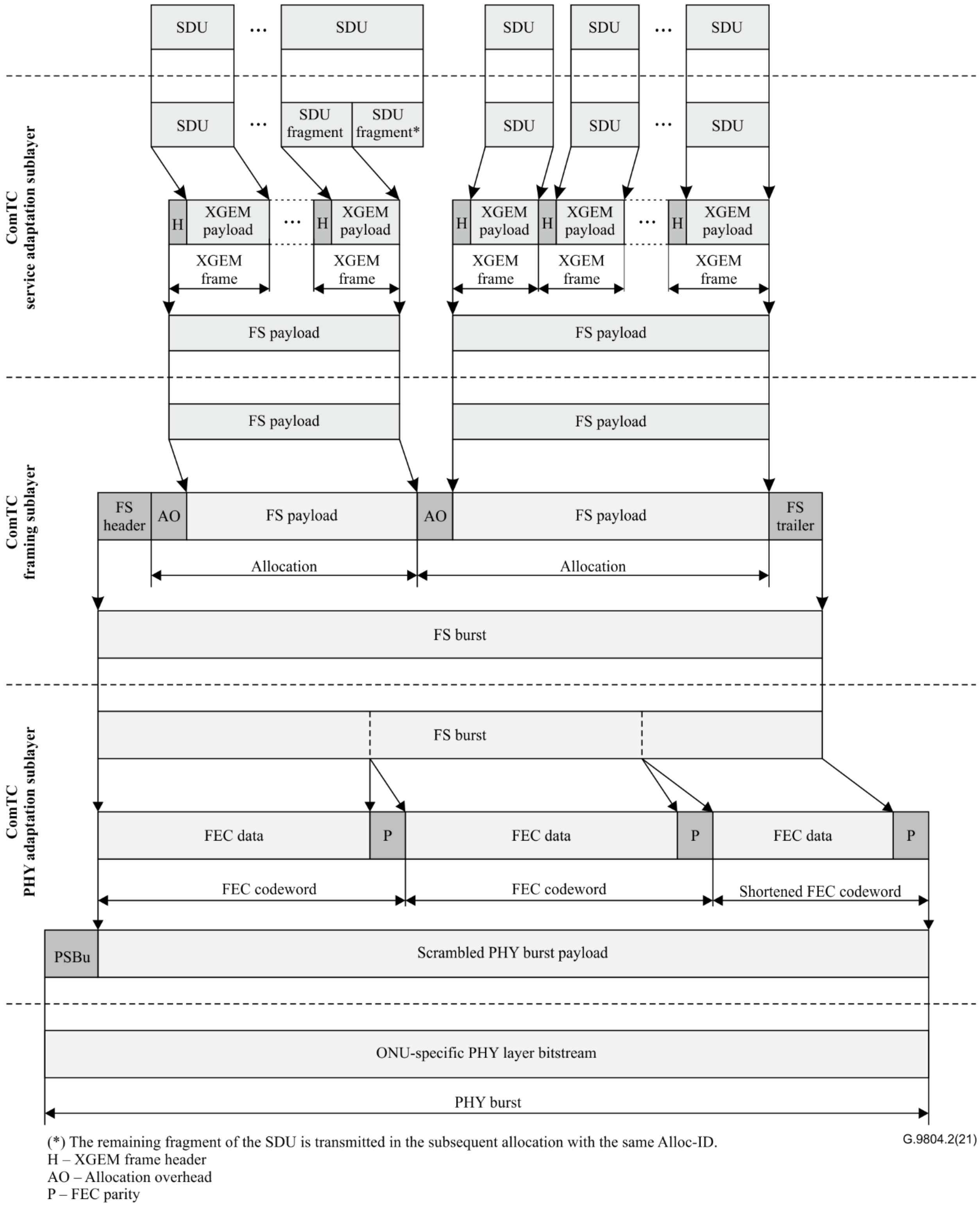


Figure 6-2 – Upstream SDU mapping into PHY bursts

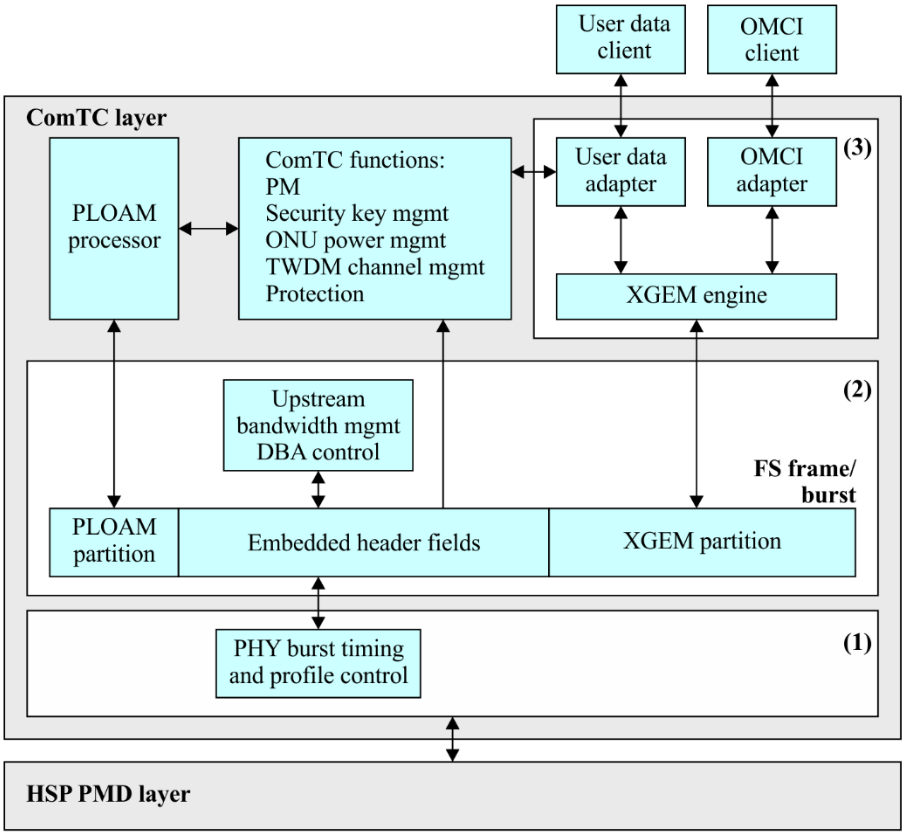
6.3 ComTC sublayer functions

The ComTC layer consists of three sublayers, which are illustrated in Figure 6-3.

The service adaptation sublayer (3) is responsible for the upper layer SDU processing and is described in clause 6.3.1.

The framing sublayer (2) constructs and parses the overhead for PON management functionality and is described in clause 6.3.2.

The PHY adaptation sublayer (1) is responsible for processing of the signal transmitted over the optical medium and is described in clause 6.3.3.



(1) ComTC PHY adaptation sublayer
(2) ComTC framing sublayer
(3) ComTC service adaptation sublayer

Figure 6-3 – Outline of ComTC information flow

6.3.1 Service adaptation sublayer

The ComTC service adaptation sublayer is responsible for the upper layer SDU encapsulation, multiplexing and delineation.

On the transmitter side, the ComTC service adaptation sublayer accepts from the clients the upper layer SDUs, represented by the user data frames and the ONU management and control interface (OMCI) traffic, performs SDU fragmentation as necessary, assigns a XGEM Port-ID to a SDU or SDU fragment, and applies the XGEM encapsulation method to obtain a XGEM frame (see clause 9). Note that the upper layer clients must shape the total amount of traffic going to any particular ONU such that the ONU's downstream traffic limitations (sustained rate and rate adaptation buffer size) are respected. If the traffic is not shaped, then downstream rate adaptation buffer overflow may occur resulting in packet loss. The XGEM frame payload may optionally be encrypted. A series of XGEM frames form a payload of a framing sublayer (FS) frame in the downstream direction or a FS burst in the upstream direction.

On the receiver side, the ComTC service adaptation sublayer accepts the payload of the FS frames or FS bursts, performs XGEM frame delineation, filters XGEM frames based on the XGEM Port-IDs, decrypts the XGEM payload if encryption has been performed by the transmitter, reassembles the fragmented SDUs and delivers the SDUs to the respective clients.

See clauses 9.1, 9.2 and 9.3 for the details of XGEM framing, XGEM frame delineation and SDU fragmentation, respectively.

As the ComTC service adaptation sublayer deals with two types of SDUs, the user data frames and OMCI messages, it can be logically decomposed into a XGEM engine, responsible for XGEM Port-ID multiplexing and filtering, and two service adapters: the user data adapter and the OMCI adapter. The user data adapter can be configured to accommodate a variety of upper layer transport interfaces.

See clause 9.4 for the most common cases of service mappings into XGEM frames.

6.3.2 Framing sublayer

The ComTC framing sublayer is responsible for the construction and parsing of the overhead fields that support the necessary PON management functionality. The ComTC framing sublayer formats are devised so that the frames, bursts, and their elements are aligned to 4-byte word boundaries, whenever possible.

On the transmitter side, the ComTC framing sublayer accepts multiple series of XGEM frames forming the FS payload from the ComTC service adaptation sublayer, and constructs the downstream FS frame or upstream FS burst by providing the overhead fields for the embedded operation, administration and maintenance (OAM) and the physical layer operation, administration and maintenance (PLOAM) messaging channel. The size of each downstream FS frame payload is obtained by subtracting the variable size of the upstream bandwidth management overhead and the PLOAM channel load from the fixed size of the downstream FS frame. In the upstream direction, a FS burst multiplexes FS payloads associated with multiple Alloc-IDs, the size of each payload being determined based on the incoming bandwidth management information (see clause 8.1.2).

On the receiver side, the ComTC framing sublayer accepts the FS frames or FS bursts, parses the FS overhead fields, extracts the incoming embedded management and PLOAM messaging flows, and delivers the FS payloads to the ComTC service adaptation sublayer. The incoming PLOAM messages are delivered to the PLOAM processor. The embedded OAM information to the extent pertaining to upstream bandwidth management, i.e., bandwidth map (BWmap) construction and parsing and dynamic bandwidth assignment (DBA) signalling is processed within the framing sublayer itself, providing partial control over the PHY adaptation sublayer (upstream PHY burst timing and profile control). The rest of the embedded OAM information is delivered to the appropriate ComTC functional entities outside of the framing sublayer, such as ONU electrical power management and performance monitoring blocks.

See clause 8.1 for the details of downstream FS frame format specification, including BWmap parsing, and clause 8.2 for the details of upstream FS burst format specification, including DBA signalling.

6.3.3 PHY adaptation sublayer

The ComTC PHY adaptation sublayer encompasses the functions that modify the bitstream modulating the optical transmitter with the goal to improve the detection, reception, and delineation properties of the signal transmitted over the optical medium.

For the transmitter in the downstream direction, the ComTC PHY adaptation sublayer accepts the FS frames from the framing sublayer, prepends the physical synchronization block appropriate for downstream physical synchronization block (PSBd) transmission, performs forward error correction (FEC) encoding, performs scrambling of the content, and provides timing alignment of the resulting bitstream. At the discretion of the OLT, the downstream PHY frame may optionally be interleaved after scrambling.

For the transmitter in the upstream direction, the ComTC PHY adaptation sublayer accepts the FS bursts from the framing sublayer, performs forward error correction (FEC) encoding, performs scrambling of the content, prepends the physical synchronization block appropriate for upstream physical synchronization block (PSBu) transmission and provides timing alignment of the resulting bitstream.

For the receiver, the ComTC PHY adaptation sublayer performs physical synchronization and delineation of the incoming bitstream, descrambles the content of the PHY frame or PHY burst, performs FEC decoding, delivering the resulting FS frames (in the downstream direction) or FS bursts (in the upstream direction) to the ComTC framing sublayer. The ComTC PHY adaptation sublayer at the ONU receiver also performs deinterleaving before descrambling if downstream interleaving has been performed by the OLT transmitter.

The details of the PSBd and PSBu overhead fields are specified in clauses 10.1.1 and 10.2.1, respectively.

The use of FEC improves the effective sensitivity and overload characteristics of the optical receiver by introducing redundancy in the transmitted bitstream and allowing to use a receiver operating at a higher bit error ratio (BER) level. FEC is specified in detail in clause 10.3.

Bitstream scrambling randomizes the transmission and helps to meet the specified consecutive identical digits (CID) tolerance. The scrambling method is specified in clause 10.4.

Interleaving mitigates the impact of burst errors on FEC error correcting capabilities. A downstream interleaving method is specified in clause 10.5.

The downstream and upstream line codes employed in an HSP system are specified in the applicable PMD Recommendations.

6.4 Management of an HSP system

The ONU control, operation, and management information in an HSP system is carried over three channels: embedded OAM, PLOAM, and OMCC (see Figure 6-4). The embedded OAM and PLOAM channels manage the functions of the PMD and ComTC layers. The OMCC carries the messages of the OMCI protocol, which provides a uniform system for managing higher (service-defining) layers.

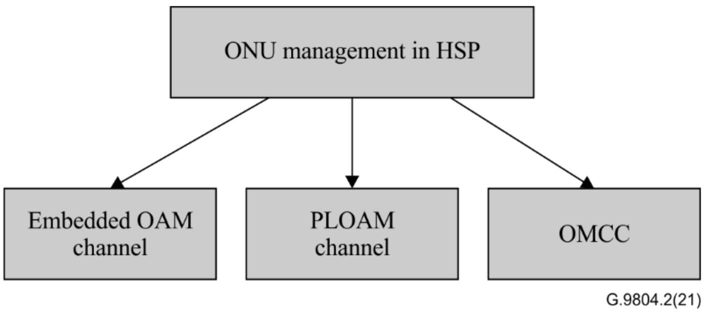


Figure 6-4 – ONU management channels and options

In addition, the inter-CT communication channel, which carries the inter-channel-termination protocol (ICTP) primitives, supports the multi-wavelength aspect of the TWDM mode of operation.

6.4.1 Embedded OAM

The embedded OAM channel is provided by the FS header fields and embedded structures of the downstream FS frame and the upstream FS burst. The embedded OAM channel offers a low-latency path for the time-urgent control information because each OAM information piece is directly mapped into a specific field of the FS header. The functions that use the embedded OAM channel include upstream PHY burst timing and profile control, bandwidth allocation, dynamic bandwidth assignment signalling, forced wake-up, and dying gasp indication. The detailed description of the FS header fields and structures involved in support of these functions is provided in clause 8 as a part of the ComTC framing sublayer specification.

6.4.2 PLOAM channel

The PLOAM channel is message based and is used for all PMD and FS management information that is not sent via the embedded OAM channel. The PLOAM message structure, message types, and detailed format specifications are provided in clause 11.

The PLOAM messages are carried in a designated partition of the downstream FS frame and the upstream FS burst (see clauses 8.1.4 and 8.2.1.4).

6.4.3 ONU management and control channel (OMCC)

The ONU management and control channel (OMCC) uses the OMCI messages to manage the service-defining layers residing above the ComTC layer. The ComTC layer must provide a XGEM-based transport interface for this management traffic, including configuration of appropriate transport protocol flow identifiers (XGEM Port-IDs). This Recommendation specifies a transfer mechanism for the OMCC. The format and detailed OMCI specification can be found in [ITU-T G.988].

The OMCI adapter at the ONU is responsible for filtering and de-encapsulating OMCI-carrying XGEM frames in the downstream direction, and for encapsulating OMCI SDUs in the upstream direction. OMCI SDUs are handed off to the logic that implements the OMCI functions.

The OMCI adapter at the OLT CT is responsible for filtering and de-encapsulating OMCI-carrying XGEM frames in the upstream direction, and for encapsulating the OMCI SDUs from the OMCI control logic into XGEM frames for transport to the ONU.

6.4.4 ICTP

In a TWDM system, in order to support such functionalities as channel profile configuration and status sharing, ONU activation, ONU wavelength channel handover, and rogue ONU mitigation, the OLT CTs need to interact with each other. This interaction between CTs takes the form of exchanging ICTP functional primitives over the abstract ICTP transportation channel. The ICTP transportation channel abstraction allows a variety of physical implementations depending on the relative location of the interacting CTs; those implementations are beyond the scope of this Recommendation. The discussion of the ICTP use cases, and functional primitives can be found in Appendix VI. The ICTP specification can be found in [b-BBF TR-352].

6.5 ComTC architecture

6.5.1 Overview

A wavelength channel pair constitutes a basic building block of an HSP system. A TWDM system is composed of multiple wavelength channel pairs; a TDM system contains one wavelength channel pair. Within each individual wavelength channel pair, the principles of TDM and TDMA apply. In the downstream direction of a wavelength channel pair, the traffic multiplexing functionality is centralized as shown in Figure 6-5. The OLT CT multiplexes XGEM frames onto the transmission medium using XGEM Port-ID as a key to identify XGEM frames that belong to different downstream logical connections. Each ONU filters the downstream XGEM frames based on their XGEM Port-IDs and processes only the XGEM frames that belong to that ONU. A multicast XGEM port can be used to carry XGEM frames to more than one ONU.

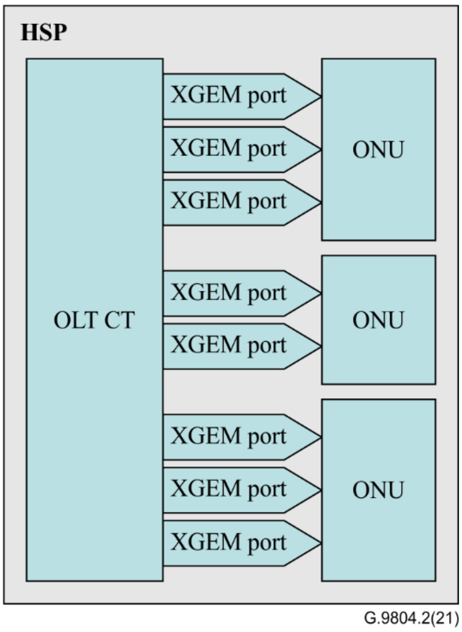


Figure 6-5 – Downstream multiplexing in HSP

In the upstream direction of a wavelength channel pair, the traffic multiplexing functionality is distributed (see Figure 6-6). The OLT CT grants upstream transmission opportunities, or upstream bandwidth allocations, to the traffic-bearing entities within the subtending ONUs. The ONU's traffic-bearing entities that are recipients of the upstream bandwidth allocations are identified by their allocation IDs (Alloc-IDs). Bandwidth allocations to different Alloc-IDs are multiplexed in time as specified by the OLT CT in the bandwidth maps transmitted downstream. Within each bandwidth allocation, the ONU uses the XGEM Port-ID as a multiplexing key to identify the XGEM frames that belong to different upstream logical connections.

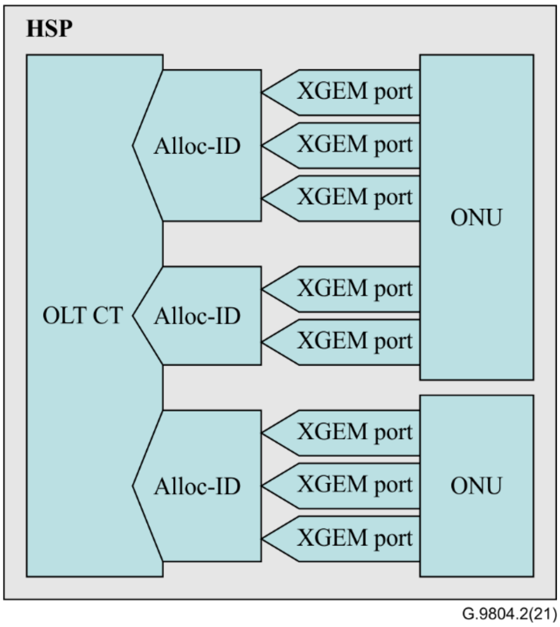


Figure 6-6 – Upstream multiplexing in HSP

6.5.2 ComTC identifiers

6.5.2.1 System identifier

System identifier (SYS ID) is a 20-bit number that identifies a specific HSP system among multiple systems under common administration. The SYS ID may be coded to include data to support administration such as an operator name, geographical location, service profile, and whether the system is for protection. It is supplied by an EMS/OSS to the OLT CT. For a TWDM system, the SYS ID is identical for all TWDM channels within the system. The OLT CT communicates the SYS ID to all subtending ONUs in the System_Profile PLOAM message (see clause 17.1). An ONU stores the SYS ID and uses it as a reference.

6.5.2.2 PON identifier

PON identifier (PON-ID) is a 32-bit structured number that uniquely identifies an OLT CT entity within an operator domain.

PON-ID consists of a 28-bit administrative label and a 4-bit downstream wavelength channel ID (DWLCH ID). The administrative label is supplied by an element management system/ operation support system (EMS/OSS) to the OLT network element. It is expected to follow some consistent physical or logical equipment numbering plan and is treated transparently by the OLT.

The PON-ID of a specific OLT CT is carried downstream within the operation control (OC) structure of the PSBd field, as described in clause 10.1.1.3. PON-ID is also included into Channel_Profile PLOAM message.

6.5.2.3 Downstream wavelength channel identifier

Downstream wavelength channel ID (DWLCH ID) is a 4-bit number that identifies a downstream wavelength channel and is equal to the ordinal number of the channel defined in the applicable TWDM PMD Recommendations.

DWLCH ID is a part of PON-ID (see clause 6.5.2.2), which is transmitted downstream within the OC structure of the PSBd field (see clause 10.1.1.3). In a fixed-channel TDM system, the default value of DWLCH ID is 0xF.

6.5.2.4 Upstream wavelength channel identifier

Upstream wavelength channel ID (UWLCH ID) is a 4-bit number that identifies an upstream wavelength channel. The specific wavelength of each upstream wavelength channel and assigning UWLCH IDs to the upstream wavelength channels is supplied to the OLT CT by an EMS/OSS. The association between the frequency specification of the selected upstream wavelength channel and the assigned UWLCH ID constitutes a part of the channel profile, which is explicitly communicated to the ONUs by the OLT CT using the Channel_Profile PLOAM message. In a fixed-channel TDM system, the default value of DWLCH ID is 0xF.

6.5.2.5 ONU identifier

ONU identifier (ONU-ID) is a 10-bit identifier that the OLT CT assigns to an ONU during the ONU's activation using the Assign_ONU-ID PLOAM message.

The ONU-ID is unique across the optical distribution network (ODN). When an ONU enters the Initial state (O1) of the ONU activation state machine (see clause 12 for the causes of the possible state transitions to O1 state), it discards the previously assigned ONU-ID along with all dependent ComTC layer configuration assignments (see Tables 12-4 and 12-5). The semantics of the ONU-ID values is shown in Table 6-1.

Table 6-1 – ONU-ID values

ONU-ID	Designation	Comment
0..1019	Assignable	Assigned by OLT CT at ONU activation; used to identify the sender of an upstream burst or a PLOAMu message and the recipient of a PLOAMd message.
1020..1022	Reserved	The number shall not be assigned to any ONU, and shall not be used as an ONU-ID.
1023	Broadcast /unassigned	Broadcast address in PLOAMd; unassigned ONU in PLOAMu.

6.5.2.6 Allocation identifier

Allocation identifier (Alloc-ID) is a 14-bit number that appears in an allocation structure of the BWmap and identifies the recipient of the corresponding upstream bandwidth allocation: a specific traffic-bearing entity within a particular ONU, or a specific contention-based function which can be used by multiple eligible ONUs. The traffic-bearing entity is either a T-CONT or the upstream OMCC.

By the *scope*, Alloc-ID can be *directed* (associated with a unique ONU) and *broadcast*, or *contention-based* (associated with a unique contention-based function).

By the *intended use*, directed Alloc-IDs are classified into *management* Alloc-IDs, used for OMCC traffic, and *data* Alloc-IDs, used for user data traffic; whereas the contention-based Alloc-IDs are classified into *activation* Alloc-IDs, which are intended for activating the ONUs that lack of and need to establish their TC layer configuration, and *pre-ranged* Alloc-IDs, which are intended for the contention-based functions that active ONUs with fully established TC layer configuration may be eligible to use.

By the *origin*, Alloc-IDs can be: *reserved* (well-known values pre-defined in this Recommendation), *default*, or *implicit* (implicitly associated with an ONU by virtue of the ONU-ID assignment and numerically equal to the assigned ONU-ID), and *assigned*, or *explicit* (assigned explicitly to a particular ONU or a particular contention-based function by means of an Assign_Alloc-ID PLOAM message).

The relationship between Alloc-IDs and their classification criteria are shown in Figure 6-7.

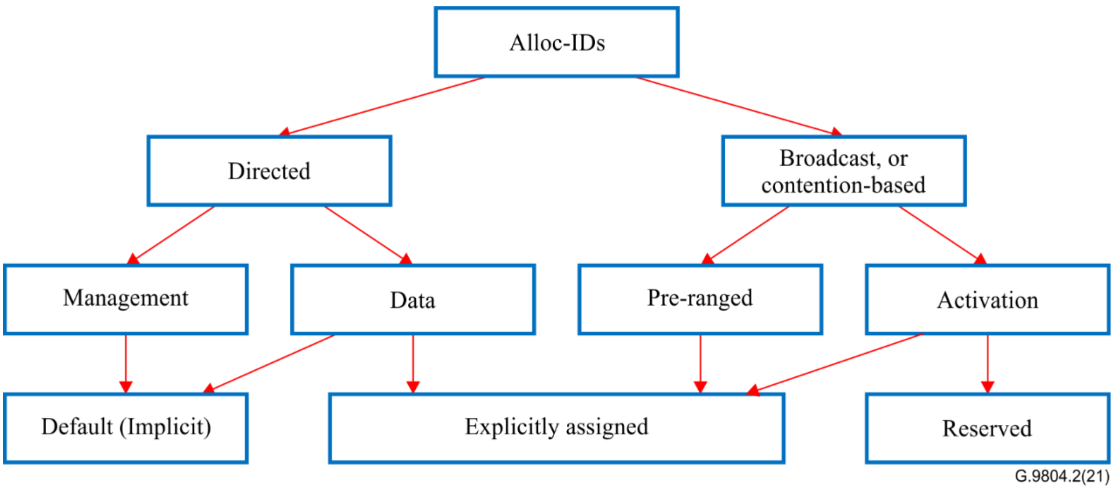


Figure 6-7 – Classification of Alloc-IDs

An Alloc-ID value is unique across the ODN for a TDM system and for all channels of a TWDM system. A directed Alloc-ID can be assigned to at most one ONU, a broadcast Alloc-ID can be assigned to at most one contention-based function.

Each ONU:

– is assigned one and only one directed default Alloc-ID, which carries the upstream OMCC traffic, may carry user data traffic, and is used for PLOAM-only allocations to a specific ONU;

– may be assigned one or more directed explicit Alloc-IDs, which are used for the user data traffic through association with a T-CONT within the given ONU;

– may use any of the broadcast reserved Alloc_IDs for the contention-based ONU activation, subject to the rate constraints specified in Table 6-2;

– may use any of the broadcast explicitly assigned Alloc-IDs for the appropriate contention-based function, subject to meeting the eligibility conditions specified in the contention-based function Table.

When an ONU enters the Initial state (O1) of the ONU activation state machine (see clause 12 for the causes of the possible state transitions to O1 state), it discards all default and explicit Alloc-ID assignments.

The Alloc-ID number space is partitioned as shown in Table 6-2.

Table 6-2 – Alloc-ID values

Alloc-ID	Designation	Comment
0..1019	Default directed	Default Alloc-ID, which is implicitly assigned with, and is equal to, the ONU-ID.
1020	Reserved Broadcast	Used by the OLT CT in a serial number grant allocation structure to indicate that any ONU transmitting at $\rho_0\phi_0$ upstream line rate which executes the serial number acquisition phase of the activation procedure may use this allocation to transmit a serial number response.
1021	Reserved Broadcast	Used by the OLT CT in a serial number grant allocation structure to indicate that any ONU transmitting at $\rho_0\phi_1$ upstream line rate which executes the serial number acquisition phase of the activation procedure may use this allocation to transmit a serial number response.
1022	Reserved Broadcast	Used by the OLT CT in a serial number grant allocation structure to indicate that any ONU transmitting at $\rho_0\phi_2$ upstream line rate which executes the serial number acquisition phase of the activation procedure may use this allocation to transmit a serial number response.
1023	Reserved Broadcast	Used by the OLT CT in a serial number grant allocation structure to indicate that any ONU transmitting at $\rho_0\phi_0$, $\rho_0\phi_1$, or $\rho_0\phi_2$ upstream line rate which executes the serial number acquisition phase of the activation procedure may use this allocation to transmit a serial number response.
1024..16383	Explicitly Assignable	If an ONU needs directed Alloc-IDs in excess of a single default Alloc-ID, the OLT CT assigns additional Alloc-IDs to that ONU by selecting a unique number from this range and communicating it to the ONU using the directed Assign_Alloc-ID PLOAM message. For activation of the ONUs with upstream line rate combinations which do not have a reserved Alloc-ID and the other contention-based

Table 6-2 – Alloc-ID values

Alloc-ID	Designation	Comment
		functions, the OLT CT dynamically assigns a contention-based Alloc-ID to be used with the specific contention-based function by selecting a unique number from this pool and communicating the assignment to all ONUs using a broadcast Assign_Alloc-ID PLOAM message.
NOTE 1 – The OLT CT may use Alloc-ID 1020, 1021 or 1022 in use cases with a single upstream rate, $\rho_0 \phi_0$, $\rho_0 \phi_1$, or $\rho_0 \phi_2$, respectively, to block accidentally connected ONUs transmitting at an incorrect upstream rate. The OLT CT may use Alloc-ID 1023 in multi-rate deployments, to reduce the discovery overhead by giving an opportunity to register simultaneously when the OLT CT uses a multi-rate receiver. NOTE 2 – At its discretion, the OLT CT may formally grant an upstream bandwidth allocation to an assignable Alloc-ID which has not been assigned to any ONU. Such an allocation causes a quiet window in the upstream transmission.		

6.5.2.7 XGEM port identifier

XGEM port identifier (XGEM Port-ID) is a 16-bit number that is assigned by the OLT CT to an individual logical connection. The XGEM Port-ID assignment to the OMCC logical connection is implicit by virtue of the ONU-ID assignment to the given ONU. The OMCC Port-ID is numerically equal to the respective ONU-ID. All other XGEM Port-ID assignments for the ONU are performed via the OMCC.

When an ONU enters the Initial state (O1) of the ONU activation state machine (see clause 12 for the causes of the possible state transitions to O1 state), it discards the default XGEM Port-ID assignment, but retains the previously assigned non-default XGEM Port-IDs (see Tables 12-4 and 12-5).

The semantics of the XGEM Port-ID values is shown in Table 6-3.

Table 6-3 – XGEM Port-ID values

XGEM Port-ID	Designation	Comment
0..1019	Default	Default XGEM Port-ID, which is implicitly assigned with and is equal to the ONU-ID. It identifies the XGEM port used by the OMCC traffic.
1020..65534	Assignable	If more than a single XGEM Port-ID is needed for an ONU, the OLT CT assigns additional Port-IDs to that ONU by selecting a unique number from this range and communicating it to the ONU using the OMCC.
65535	Idle	Reserved for Idle XGEM Port-ID

6.5.2.8 Channel partition index

In a TWDM system, an operator may subdivide the set of TWDM channels into non-overlapping subsets *using* an arbitrary criterion, such as commonality of service profile, equipment or geographical location. Each such channel subset is known as a channel partition and is identified by an index which is unique within the TWDM system. Channel partition index (CPI) is contained in the Channel_Profile PLOAM message. In a TDM system, CPI defaults to 0.

As an operational attribute, an ONU carries a CPI, storing it in a non-volatile memory and ensuring that its value is retained through ONU reactivation, warm and cold reboot, power cycle, MIB reset, and/or power loss. The value of ONU's CPI is read/write-accessible via OMCI. If the OLT changes the ONU's specific CPI value via OMCI, the OLT is expected to reactivate the ONU immediately thereafter. The ONU's CPI value is only checked against the current channel partition at the start of an activation cycle.

An ONU's CPI can be specific (non-zero) or default (zero). An ONU with a specific CPI may activate only on channels whose Channel_Profile CPI matches the CPI of the ONU. An ONU with a default CPI can attempt to activate on a channel belonging to any channel partition, and learns its specific channel partition association at the time of ONU-ID assignment. An ONU with a specific CPI refuses an instruction to tune to a channel belonging to a different channel partition than that of the ONU.

Within a channel partition with a non-zero index *P*, an activation or handover is available to ONUs with the default CPI = 0 or specific CPI = *P*. Within a channel partition with a zero index, an activation or handover is available only to ONUs with the default CPI = 0.

When an ONU with a specific CPI, that has commenced a search for a channel partition for activation, finds a downstream wavelength channel belonging to a non-matching channel partition, it starts a timer marking pre-specified interval T_{CPI}. If the ONU cannot find a channel belonging to the matching channel partition by the expiration of the timer, the ONU resets its CPI in non-volatile memory to the default value (zero) in order to waive the CPI restriction. The suggested value of T_{CPI} is 5 minutes.

6.6 Media access control

For a wavelength channel pair in an HSP system, the OLT CT provides media access control for the upstream traffic. In the basic concept, each downstream PHY frame contains a BWmap that indicates the location for an upstream transmission by each ONU in the corresponding upstream PHY frame. The media access control concept is illustrated in Figure 6-8.

The OLT CT transmits a downstream PHY frame every 125 μs. Because of the varying fibre distance, each PHY frame reaches different ONUs at generally different time instants. With each received downstream PHY frame, the ONU associates it with the corresponding upstream PHY frame. The individual equalization delays established in the course of ONU ranging serve to synchronise all ONUs to the same reference at the start of each upstream PHY frame in such a way that upstream transmissions by any two ONUs, occurring at the same offset with respect to the start of the upstream PHY frame, would reach the OLT CT at the same time.

For each PHY frame, the OLT CT creates and transmits downstream a BWmap that specifies a sequence of non-overlapping upstream transmissions by different ONUs. Note that for co-existence schemes based on TDMA upstream sharing in the same wavelength as shown in Figure 7-6 of [ITU-T G.9804.1], the BWmap has to be coordinated across the HSP and XG(S)-PON CTs. A BWmap contains a number of allocation structures, each allocation structure being addressed to a particular Alloc-ID of a specific ONU. A sequence of one or more allocation structures addressed to Alloc-IDs that belong to the same ONU forms a burst allocation series. Each burst allocation series contains a start pointer indicating the beginning of the burst within the upstream PHY frame and a sequence of grant sizes that the ONU is allowed to transmit. The start pointers refer to offsets within the upstream PHY frame (on the ComTC PHY adaptation sublayer), whereas the grant sizes pertain to the payload of FS frame (on the ComTC framing sublayer). The start pointers and grant sizes are expressed in units whose granularity depend on the upstream line rate of the target ONU (see clause 8.1.2). The OLT CT may grant higher or lower effective data rates by controlling the size and frequency of the grants and may modulate the effective data rate via a dynamic scheduling.

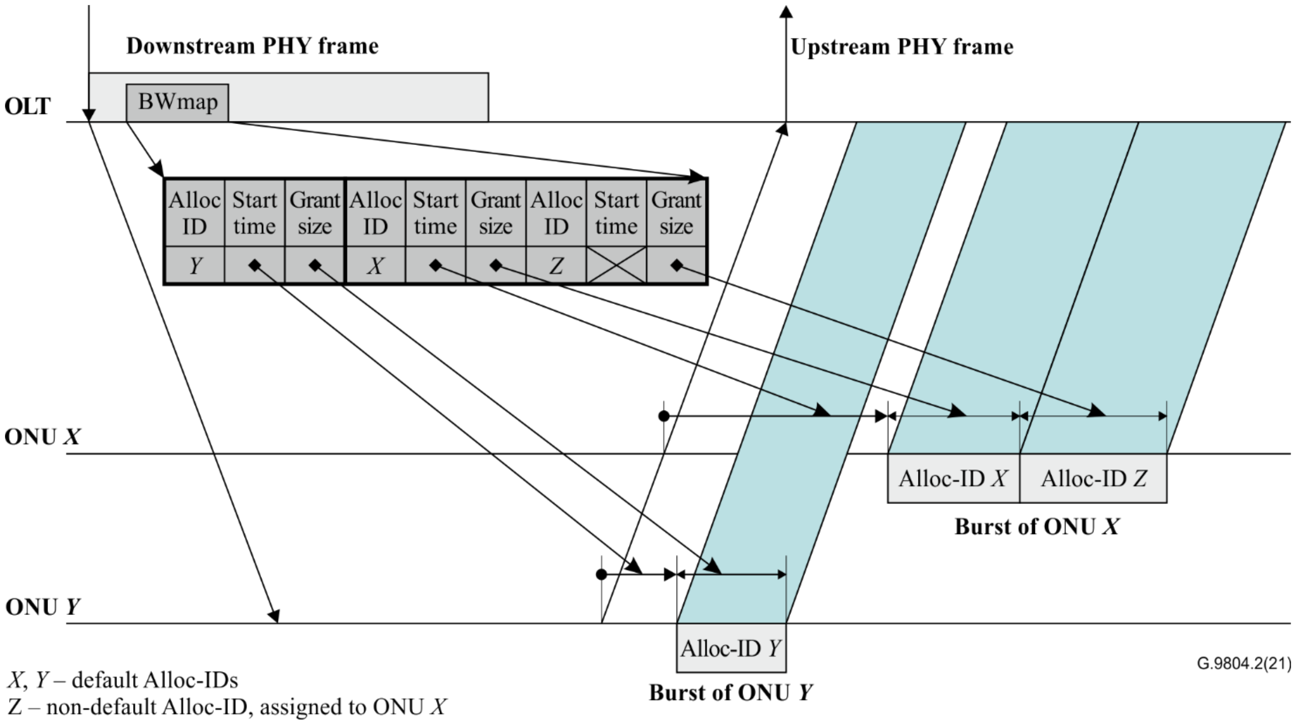


Figure 6-8 – ComTC media access control concept

The use of BWmap parameters is discussed more precisely in clause 8.1.2. The details of the PON timing relationships can be found in clause 13.1.

7 Resource allocation and quality of service

The access-specific quality of service (QoS) capabilities are an integral part of the end-to-end QoS provisioning mechanisms. They are necessary, but they are not sufficient to ensure that the QoS objectives of end-to-end traffic flows are met. In a ComTC-based optical access network, QoS capabilities are supported by the OLT CT and the ONU network elements. QoS capabilities are associated with the ways to allocate available resources to individual and/or aggregated traffic flows. Available resources may include processing capacity, buffer space, downstream and upstream wavelength channels, and digital bandwidth of each wavelength channel.

The remainder of this clause is dedicated to resource allocation within an individual wavelength channel with a single upstream line rate. The issues associated with the dynamic assignment of the wavelength channels as well as the dual upstream line rate support are left to the implementor's discretion. The implementation should resolve them consistently with the base case considered in this clause. Ressource allocation in TDMA co-existence scenarios across generations of systems is for future study.

7.1 Principles of downstream and upstream resource allocation

A traffic flow is provisioned with a specific set of downstream and upstream service parameters. These parameters may be represented by a traffic descriptor.

7.1.1 Forms of traffic descriptor

In its conventional form, the traffic descriptor is composed of the bandwidth parameters and is generally represented as:

$$D = \left\langle R_F, R_A, R_M, \chi_{AB}, P, \omega \right\rangle \quad (7\text{-}1)$$

where:

R_F: Fixed bandwidth [bit/s];

R_A: Assured bandwidth [bit/s];

R_M: Maximum bandwidth [bit/s];

χ_{AB}: Ternary eligibility indicator for additional bandwidth assignment: {none, non-assured (NA), best-effort (BE)};

P: Priority for best-effort bandwidth assignment;

ω: Weight for best-effort bandwidth assignment.

Fixed bandwidth, $R_F \geq 0$, represents the reserved portion of the link capacity that is allocated to the given traffic flow, regardless of its traffic demand and the overall traffic load conditions.

Assured bandwidth, $R_A \geq 0$, represents a portion of the link capacity that is allocated to the given traffic flow as long as the flow has unsatisfied traffic demand, regardless of the overall traffic conditions.

Maximum bandwidth, $R_M > 0$, represents the upper limit on the total bandwidth that can be allocated to the traffic flow under any traffic conditions.

In its extended form, the traffic descriptor is composed of the bandwidth parameters and the timing parameters and is represented as:

$$D = \langle R_F, R_A, R_M, \chi_{AB},\ P, \omega,\ T_{JT}, T_{BDT},\ T_{PST} \rangle \qquad (7\text{-}1a)$$

where, additionally:

Jitter tolerance, $T_{JT} > 0$, represents the minimum time interval over which an active traffic flow shall receive an allocation of the size corresponding at least to the assigned bandwidth (see clause 7.2.4).

Bandwidth assignment delay tolerance, $T_{BDT} > 0$, represents the maximum delay that a previously inactive traffic flow may experience from the moment it becomes active to the moment it receives an allocation of the size corresponding at least to the assigned bandwidth.

Protection switching delay tolerance, $T_{PST} > 0$, represents the maximum delay that an ONU that has switched to a pre-configured protection channel may experience from the moment it attains downstream synchronization in the target TWDM channel to the moment it receives an allocation to its default Alloc-ID. T_{PST} is applicable to TWDM only.

The implementations predating the present amendment are not required to support the extended form of the traffic descriptor. For the subsequent implementations, the support of the extended form of the traffic descriptor is subject to operator requirements. The implementations not supporting the extended form of the traffic descriptor are expected to have well understood default values or bounds of the timing parameters, based on the system design.

7.1.1 Traffic descriptor constraints

A correctly formed traffic descriptor should satisfy the following three invariant restrictions:

$$\begin{gathered} R_M \geq R_F + R_A \\ \text{if } \chi_{AB} = NA, \text{ then } R_M > R_F + R_A > 0 \\ \text{if } \chi_{AB} = BE, \text{ then } R_M > R_F + R_A \geq 0 \end{gathered} \qquad (7\text{-}2)$$

In addition, the overall traffic specification should satisfy the basic stability condition:

$$\sum_i \left(R_F^i + R_A^i\right) \le C \tag{7-3}$$

where the summation is over the set of all upstream or downstream traffic flows on the wavelength channel, and C is the effective capacity (i.e., excluding overheads) of the upstream or downstream interface, respectively.

The specified general form of traffic descriptor allows support of both rate-based service disciplines and priority-based service disciplines. By setting certain descriptor components to zero (bandwidth parameters) or identical values (priority and weight parameters), the system operator can effectively specify the required service discipline. The upstream and downstream traffic flows may be specified with different subsets of descriptor components. In particular, the fixed bandwidth parameter is important in a distributed scheduling environment, where it serves to mitigate the communication latency between the network elements hosting, respectively, the scheduler and the traffic queues, and may not be applicable in the downstream direction where scheduling is centralized.

If necessary, two or more traffic flows may be considered as a single aggregate flow. The traffic descriptor of the aggregate flow is constructed by the system from the individual traffic descriptors of the constituent traffic flows. The bandwidth parameters of the aggregate flow traffic descriptor (denoted by an asterisk) are expected to satisfy:

$$\begin{gathered} R_F^* + R_A^* = \sum_j \left(R_F^j + R_A^j\right) \\ \max_j R_M^j \le R_M^* \le \sum_j R_M^j \end{gathered} \tag{7-4}$$

where the superscript j denotes a parameter of the jth constituent traffic descriptor. Determination of the parameter values of the aggregate flow traffic descriptor from its constituent traffic descriptors is beyond the scope of this Recommendation.

In the downstream direction, it is the responsibility of the OLT CT to provide QoS-aware traffic management (including, as applicable, buffer management, traffic scheduling and shaping) of XGEM Port-ID traffic flows based on the respective traffic descriptors, availability of memory and bandwidth resources and dynamic traffic conditions. Because this function is internal to the OLT, it is beyond the scope of this Recommendation.

In the upstream direction, an aggregate traffic descriptor is constructed for each transmission container (T-CONT) based on the service specifications of the XGEM Port-ID flows multiplexed onto that T-CONT. It is the responsibility of the OLT CT to provide QoS-aware traffic management of the aggregate traffic flows associated with the T-CONTs based on the respective aggregate service specifications, the upstream bandwidth availability and, possibly, the information obtained through upstream traffic monitoring and/or ONU status reporting. For each individual T-CONT, it is the responsibility of the ONU to which the T-CONT belongs to provide QoS-aware traffic management of the constituent XGEM Port-ID traffic flows based on the respective XGEM Port-ID service specifications, resource availability, and dynamic traffic conditions.

The ONU upstream traffic management facilities supporting resource allocation and QoS may include ingress traffic policing, traffic shaping, and XGEM Port-ID flow scheduling within a T-CONT. The specification of these functions is beyond the scope of this Recommendation.

The remainder of this clause is concerned specifically with the upstream traffic management, and any reference to provisioned traffic parameters pertains to aggregate traffic descriptors associated with Alloc-IDs.

7.2 Dynamic bandwidth assignment overview

Dynamic bandwidth assignment (DBA) is the process by which the OLT allocates upstream transmission opportunities to the traffic-bearing entities within the ONUs of a given wavelength channel, based on the dynamic indication of their activity and their configured traffic contracts. The activity status indication can be either explicit through buffer status reporting, implicit through transmission of idle XGEM frames during the upstream transmission opportunities, or both.

In comparison with static bandwidth assignment, the DBA mechanism improves upstream bandwidth utilization by reacting adaptively to the ONUs' burst traffic patterns. The practical benefits of DBA are twofold. First, the network operator can add more subscribers to the access network due to more efficient bandwidth use. Second, subscribers can enjoy enhanced services, such as those requiring variable rate with peaks extending beyond the levels that can reasonably be allocated statically.

7.2.1 DBA abstraction

The recipient entity of the upstream bandwidth allocation is represented by an allocation ID (Alloc-ID). Regardless of the number of Alloc-IDs assigned to each ONU, the number of XGEM ports multiplexed onto each Alloc-ID, and the actual physical and logical queuing structure implemented by the ONU, the OLT CT models the traffic aggregate associated with each subtending Alloc-ID as a single logical buffer. Furthermore, for the purpose of bandwidth assignment, the OLT CT considers all Alloc-IDs specified for the given wavelength channel to be independent peer entities on the same level of logical hierarchy. Figure 7-1 illustrates DBA abstraction for a wavelength channel.

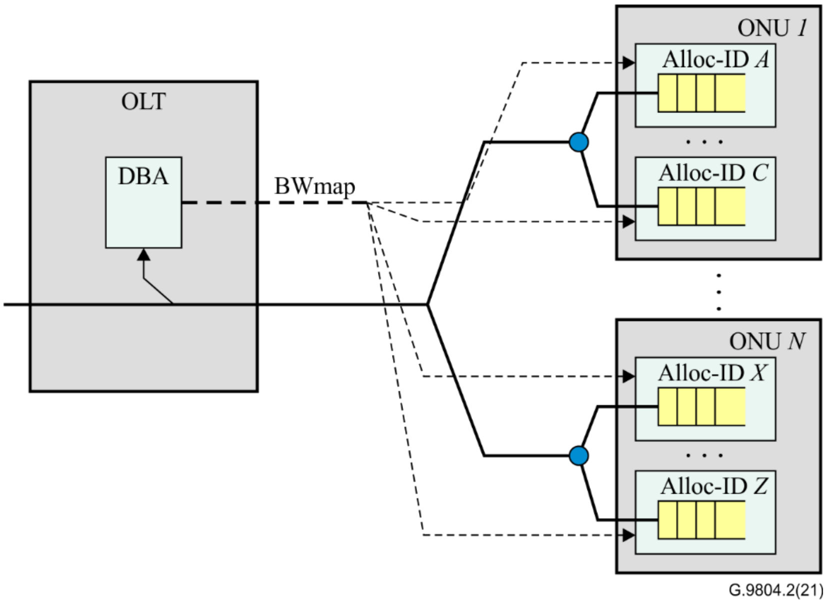


Figure 7-1 – DBA abstraction

For each Alloc-ID logical buffer, the DBA functional module of the OLT CT infers its occupancy by collecting in-band status reports, or by observing the upstream idle pattern, or both. The DBA function then provides input to the OLT upstream scheduler, which is responsible for generating the bandwidth maps (BWmaps). The BWmap specifies the size and timing of the upstream transmission opportunities for each Alloc-ID, and is communicated to the ONUs in-band with the downstream traffic.

7.2.2 DBA functional requirements

Dynamic bandwidth assignment encompasses the following functions. These functions apply on the level of individual Alloc-IDs and their provisioned bandwidth component parameters:

1) Inference of the logical upstream transmit buffer occupancy status.
2) Update of the instantaneously assigned bandwidth according to the inferred buffer occupancy status within the provisioned bandwidth component parameters.
3) Issue of allocations according to the updated instantaneous bandwidth.
4) Management of the DBA operations.

The OLT CT is required to support DBA.

7.2.3 DBA methods

Depending on the ONU buffer occupancy inference mechanism, three DBA methods can be distinguished:

– status reporting (SR) DBA is based on explicit buffer occupancy reports that are solicited by the OLT CT and submitted by the ONUs in response;
– traffic monitoring (TM) DBA is based on the OLT CT's observation of the idle XGEM frame pattern and its comparison with the corresponding bandwidth maps.
– cooperative (CO) DBA is based on the application-level upstream scheduling information provided by the OLT-side external equipment, such as a BBU in a wireless transport system.

The OLT CT shall support a combination of TM and SR DBA methods and may additionally support the CO DBA method. The OLT CT shall be capable of performing the DBA functions of clause 7.2.2 in an efficient and fair manner. The specific efficiency (see clause 7.4) and fairness (see clause 7.3) criteria can be based on overall channel bandwidth utilization, the individual ONU's performance, tested against the corresponding objectives, and comparative performance of multiple ONUs.

An ONU shall support DBA status reporting, and shall transmit upstream DBA reports as instructed by the OLT CT. The status reporting DBA method involves in-band signalling between the OLT CT and the ONUs, which is an inherent part of the ComTC specification. SR DBA signalling is discussed in detail in clause 8.2.2.

Unlike SR and TM methods, the CO DBA does not require any upstream grant allocation for upstream status reporting or activity testing.

The algorithmic details of how the OLT CT applies the reported or inferred status information, the entire specification of the traffic monitoring DBA method, as well as the details of the OLT CT upstream scheduler, which is responsible for the BWmap generation, are outside the scope of the Recommendation, and their implementation is left to the OLT vendor.

7.2.4 DBA engine

The unified conceptual representation of the DBA engine is shown in Figure 7-2.

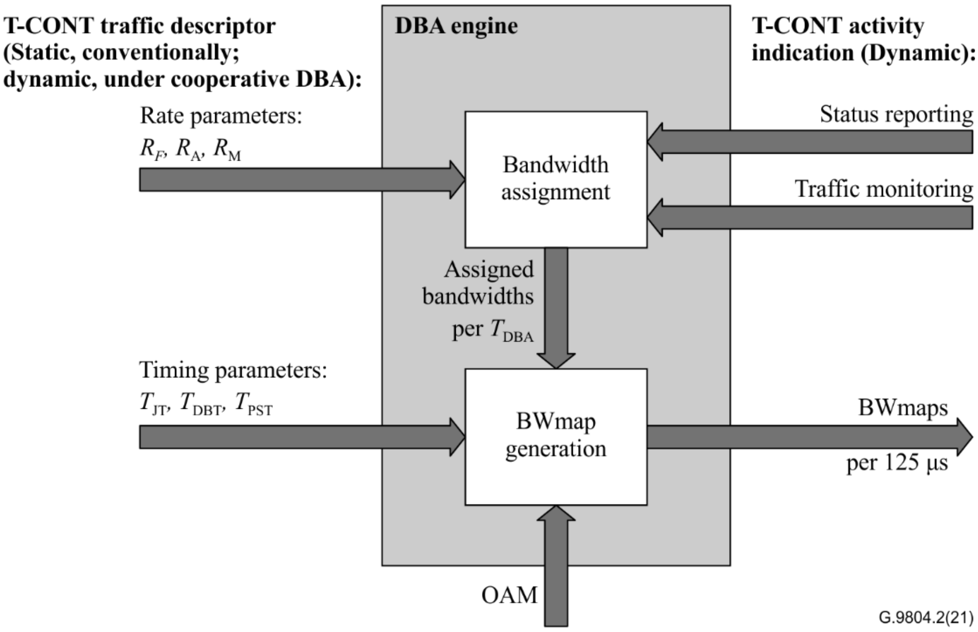


Figure 7-2 –DBA engine conceptual representation

The DBA engine consists of the fair bandwidth assignment and BWmap generation components. The fair bandwidth assignment component uses the rate parameters of T-CONT traffic descriptors along with the dynamic indication of the traffic load obtained through ONU status reporting (SR) and upstream traffic monitoring (TM) to compute a set of assigned bandwidths. The assigned bandwidth calculation is repeated every DBA cycle according to the reference model discussed in clause 7.3. The assigned bandwidths are then supplied to the BWmap Generator component, which uses them, along with the timing parameters of T-CONT traffic descriptors and the local OAM input, to generate a BWmap once every 125 μs. The OAM input includes indications for providing the directed upstream allocations for the PLOAMu messages, as well as providing minimal allocations for the ONUs under wavelength protection, allocation minimization for the ONUs under power management control (see clause 16), and providing the broadcast allocations along with the selective withdrawal of directed allocations under the contention-based operation (see clause 7.5).

If the DBA engine obtains the dynamic traffic load information exclusively via the fibre interface using the SR and TM methods, the T-CONT traffic descriptor parameters remain static. If in addition the DBA engine uses the cooperative interface (CO) method, the application-level upstream scheduling information from the OLT-side external equipment is applied to modulate the rate and timing parameters of T-CONT traffic descriptors over time, effectively making them dynamic.

7.3 Reference model of dynamic bandwidth assignment

7.3.1 Summary of notation

The following additional notation is employed throughout this clause:

A The amount of traffic arriving to a buffer [bit].

B Logical buffer occupancy [bit].

R Total assigned bandwidth, dynamic [bit/s].

R_G Assigned guaranteed bandwidth, dynamic [bit/s].

R_L Offered traffic load, dynamic [bit/s].

R_{NA} Assigned non-assured bandwidth, dynamic [bit/s].

R_{BE} Assigned best-effort bandwidth, dynamic [bit/s].

S_{NA} Surplus bandwidth available for non-assured assignment, dynamic [bit/s].

S_{BE} Surplus bandwidth available for best-effort assignment, dynamic [bit/s].

Where appropriate, a superscript indicates a specific Alloc-ID.

7.3.2 Offered traffic load

Each Alloc-ID can be dynamically characterized by its offered traffic load, $R_L(t)$, which is defined as the average rate at which the logical buffer of an Alloc-ID would have to be served in order to be drained in certain fixed time Δ, representing a system constant (equal to at least one, and eight-frame times being suggested.):

$$R_L(t) = \frac{B(t) + A(t, t + \Delta)}{\Delta} \quad (7\text{-}5)$$

where $B(t)$ is the logical buffer occupancy at time t, and the optional term $A(t, t + \Delta)$ represents new arrivals to the buffer during the interval $(t, t + \Delta)$. Note that $A(t, t + \Delta)$ may be excluded from the definition if strictly non-predictive reference is desired.

7.3.3 Components of assigned bandwidth

The bandwidth $R^i(t) \geq 0$, dynamically assigned to Alloc-ID i under the present reference model, is composed of the guaranteed and additional components (see Figure 7-3). The guaranteed bandwidth, $R^i_G(t)$, can be in the form of fixed bandwidth and assured bandwidth. The additional bandwidth can be either in non-assured form, $R^i_{NA}(t)$, or best-effort form, $R^i_{BE}(t)$:

$$R^i(t) = R^i_G(t) + R^i_{NA}(t) \quad (7\text{-}6a)$$

for Alloc-IDs i with χ^i_{AB} = NA,

$$R^i(t) = R^i_G(t) + R^i_{BE}(t) \quad (7\text{-}6b)$$

for Alloc-IDs i with χ^i_{AB} = BE,

$$R^i(t) = R^i_G(t) \quad (7\text{-}6c)$$

for Alloc-IDs i with χ^i_{AB} = None.

For the guaranteed bandwidth assignment, the reference model employs a criterion based on the provisioned rate parameters. The fixed portion of the guaranteed bandwidth is assigned statically. The assured portion of the guaranteed bandwidth is assigned dynamically based on the offered load of the specific Alloc-ID. For the additional bandwidth assignment, the reference model supports both a rate-proportional criterion and a criterion based on provisioned priority and weights. The additional bandwidth is assigned dynamically (within the shaded area of Figure 7-3) based on the offered load of the specific Alloc-ID and the overall traffic conditions.

The reference model effectively introduces a strict priority hierarchy among the forms of assigned bandwidth:

1) Fixed bandwidth (highest priority).
2) Assured bandwidth.
3) Non-assured bandwidth.
4) Best-effort bandwidth (lowest priority).

First, the OLT CT should assign the fixed bandwidth to all Alloc-IDs on the wavelength channel, regardless of their individual offered loads and the overall traffic conditions. Then the OLT CT completes the guaranteed bandwidth component assignment by allocating assured bandwidth to each Alloc-ID until either the respective provisioned level R_A is reached or the traffic demand is satisfied. After that, the OLT CT allocates non-assured bandwidth components to the eligible unsaturated

Alloc-IDs until either all the Alloc-IDs reach their saturation level (that is, the lesser of the respective maximum bandwidth R_M and offered load $R_L(t)$), or the surplus bandwidth pool $S_{NA}(t)$ is exhausted. Finally, the OLT CT allocates best-effort bandwidth components to the eligible unsaturated Alloc-IDs.

The reference model requires that, for all Alloc-ID *i*, at all times when the offered traffic load $R^i_L(t)$ exceeds the provisioned fixed level R^i_F, the assigned bandwidth $R^i(t)$ should satisfy the conservation condition:

$$R^i(t) \leq \min\left\{R^i_M; R^i_L(t)\right\} \tag{7-7}$$

7.3.4 Guaranteed bandwidth assignment

As long as the basic stability condition of Equation (7-3) is satisfied, the guaranteed component of the dynamically assigned bandwidth is given by:

$$R^i_G(t) = \min\left\{R^i_F + R^i_A; \max\left\{R^i_F; R^i_L(t)\right\}\right\} \tag{7-8}$$

$R^i_G(t)$ is available to the given Alloc-ID regardless of the overall traffic load conditions. Thus, R^i_F is the lower bound on assigned guaranteed bandwidth $R^i_G(t)$, and $R^i_A + R^i_F$ is the upper bound.

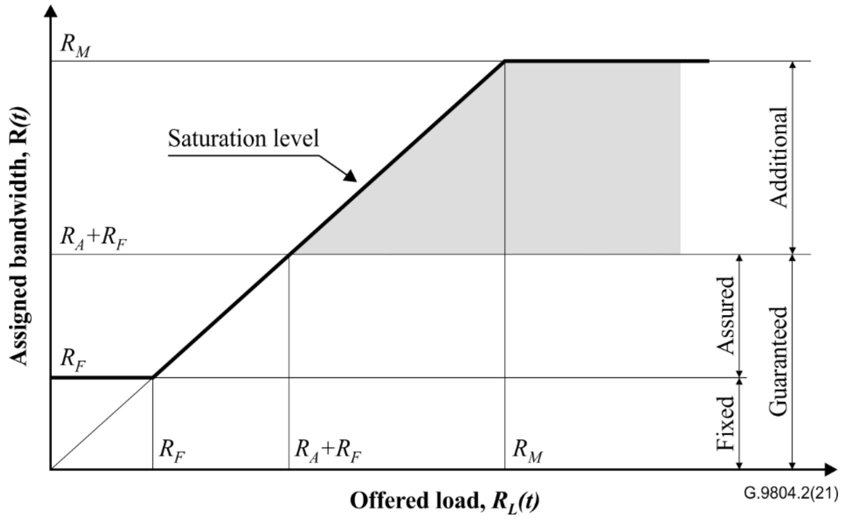


Figure 7-3 – Assigned bandwidth components with respect to offered load

7.3.5 Rate-proportional assignment of additional bandwidth

To realize the rate-proportional assignment of the additional bandwidth, the Alloc-IDs are provisioned with appropriate individual R^i_F, R^i_A, and R^i_M parameters. The priority and weight parameters for all Alloc-IDs are set to identical values. The additional bandwidth eligibility can be provisions to either value (NA, BE, none).

Non-assured bandwidth, R_{NA}, is a form of additional bandwidth that the OLT CT may dynamically assign to an eligible Alloc-ID in proportion to the sum of that Alloc-ID's fixed and assured bandwidths.

The amount of surplus bandwidth that can participate in the non-assured bandwidth assignment is equal to the portion of the uplink capacity that remains available after the guaranteed bandwidth components have been dynamically assigned for all Alloc-IDs. This amount is given by the following expression:

$$S_{NA}(t) = C - \sum_i R^i_G(t) \tag{7-9}$$

where $R^i_G(t)$ is specified by Equation (7-8).

The surplus bandwidth $S_{NA}(t)$ is shared among the eligible (χ_{AB} = NA) Alloc-IDs so that:

1) the bandwidth conservation condition of Equation (7-7) holds, and either

2.1) for each Alloc-ID i, the assigned bandwidth satisfies the saturation criterion:

$$R^i(t) = \min\left\{R_M^i ; \max\left\{R_L^i(t); R_F^i\right\}\right\} \tag{7-10}$$

or:

2.2) $S_{NA}(t)$ is exhausted and at most one Alloc-ID remains unsaturated, or:

2.3) $S_{NA}(t)$ is exhausted and for any two eligible unsaturated Alloc-IDs i and j, the assigned non-assured bandwidths satisfy the fairness condition:

$$\frac{R_{NA}^i(t)}{R_F^i + R_A^i} = \frac{R_{NA}^j(t)}{R_F^j + R_A^j} \tag{7-11}$$

Best-effort bandwidth is a form of additional bandwidth that the OLT CT may dynamically assign to an eligible Alloc-ID in proportion to the non-guaranteed portion of that Alloc-ID's provisioned maximum bandwidth.

The Alloc-IDs eligible for the best-effort assignment receive additional bandwidth only if all the Alloc-IDs eligible for the non-assured assignment have been saturated. The amount of surplus bandwidth that can participate in the best-effort bandwidth assignment is equal to the portion of the uplink capacity that remains available after all the Alloc-IDs eligible for the non-assured bandwidth assignment have been saturated, and all the other Alloc-IDs have been assigned their respective guaranteed bandwidth components. This amount is given by the following expression:

$$S_{BE}(t) = C \;-\; \sum_{i\in\left\{\chi_{AB}^i = NA\right\}} R^i(t) - \sum_{i\in\left\{\chi_{AB}^i \neq NA\right\}} R_G^i(t) \tag{7-12}$$

Here $R^i_G(t)$ is specified by Equation (7-8), and $R^i(t)$ by the saturation criterion in Equation (7-10).

The surplus bandwidth $S_{BE}(t)$ is shared among the eligible (χ_{AB} = BE) Alloc-IDs so that:

1) the bandwidth conservation condition of Equation (7-7) holds, and either

2.1) for each Alloc-ID i, the assigned bandwidth satisfies the saturation criterion of Equation (7-10),

or:

2.2) $S_{BE}(t)$ is exhausted and at most one Alloc-ID remains unsaturated, or:

2.3) $S_{BE}(t)$ is exhausted and for any two eligible unsaturated Alloc-IDs i and j, the assigned best-effort bandwidths satisfy the fairness condition:

$$\frac{R_{BE}^i(t)}{R_M^i - \left(R_F^i + R_A^i\right)} = \frac{R_{BE}^j(t)}{R_M^j - \left(R_F^j + R_A^j\right)} \tag{7-13}$$

7.3.6 Additional bandwidth assignment based on priority and weights

To realize the additional bandwidth assignment based on priority and weights, the Alloc-IDs are provisioned with appropriate individual P_i and ω_i parameters. The bandwidth parameters for all Alloc-IDs within each P_i level are set to identical values. The additional bandwidth eligibility can be provisions to either BE or none.

The amount of surplus bandwidth that can participate in the best-effort bandwidth assignment is equal to the portion of the uplink capacity that remains available after the guaranteed bandwidth components have been dynamically assigned for all Alloc-IDs. This amount is given by the following expression:

$$S_{BE}(t) = C - \sum_i R_G^i(t) \tag{7-14}$$

where $R^i_G(t)$ is specified by Equation (7-8).

The surplus bandwidth $S_{BE}(t)$ is shared among the eligible (χ_{AB} = BE) Alloc-IDs so that:

1) the bandwidth conservation condition of Equation (7-7) holds, and either

2.1) for each Alloc-ID i, the assigned bandwidth satisfies the saturation criterion of Equation (7-10),

or:

2.2) $S_{BE}(t)$ is exhausted and the following two statements hold:

as long as at least one eligible Alloc-ID i with provisioned priority level P_i remains unsaturated, the assigned best-effort bandwidth share of any Alloc-ID with a logically lower provisioned priority level is zero;

as long as two eligible Alloc-IDs i and j with identical provisioned priority levels $P_i = P_j$ remain unsaturated, their assigned best-effort bandwidth shares satisfy the fairness condition:

$$\frac{R_{BE}^i(t)}{\omega_i} = \frac{R_{BE}^j(t)}{\omega_j} \tag{7-15}$$

7.3.7 Timing control of assigned bandwidth

The optional timing parameters of the extended traffic descriptor allow access network operators to control the temporal aspect of the process that allocates transmission opportunities to the traffic flows based on the assigned bandwidth. This improves throughput and facilitates support of the delay/jitter-sensitive applications.

Once the assigned bandwidth of a traffic flow is obtained using the rate-based model, the Jitter tolerance parameter, T_{JT}, effectively determines the frequency of grant allocation to the given flow. For the traffic flows that are not sensitive to delay and jitter, the larger T_{JT} stipulates fewer bursts and reduces losses to the burst mode overhead. However, T_{JT} cannot become so large that it causes the ONU's upstream rate adaptation buffer to underflow. The OLT can discover the ONU's capabilities via the OMCI, and act accordingly. For the delay/jitter sensitive applications, the shorter T_{JT} increases the frequency of burst allocations, reducing delay and jitter at the expense of diminished overall upstream throughput due to extra burst mode overhead. The resulting trade-off is a subject to evaluation by the operator.

The Bandwidth assignment delay tolerance parameter, T_{BDT}, effectively determines the frequency of grant allocation to a traffic flow that has shown zero or low offered load in the upstream direction. Such grants are needed to execute Status reporting and Traffic monitoring DBA methods.

The Protection switching delay tolerance parameter, T_{PST}, is applicable to TWDM only and effectively determines the frequency of grants allocated to an ONU by its Protection OLT CT channel, while the ONU is still operating in its primary TWDM channel.

The implementations are expected to support timing parameter configurability based on a finite set of representative values, rather than on a continuous value range.

7.4 DBA performance requirements

In practice, the OLT DBA algorithm does not have complete knowledge of the system state. In particular, instead of the true offered loads $R_L^i(t)$, it operates on the basis of estimates, $\hat{R}_L^i(t)$, which are obtained from the DBRu reports and traffic monitoring results by methods outside the scope of this Recommendation. This clause recommends several DBA performance criteria that allow to evaluate a practical DBA implementation against the reference model of clause 7.3.

7.4.1 Stationary bandwidth assignment

In a system where Alloc-ID activity and traffic demand status remain constant, the assigned bandwidth to an Alloc-ID is measured as an average over the BWmaps transmitted in any sequence of K consecutive downstream frames, where K is chosen large enough to average the allocations that may vary from frame to frame.

Target performance

The OLT DBA algorithm should ensure that the stationary assigned bandwidth for each subtending unsaturated Alloc-ID is at least equal to the respective fixed plus assured bandwidth and is within specified bounds (e.g., 10%) of the dynamic value computed, based on the reference model of clause 7.3.

7.4.2 Assured bandwidth restoration time

This is the worst-case time interval, as observed at the ONU, from the moment an Alloc-ID, which is entitled to receive assured bandwidth assignment but has not been receiving it due to insufficient traffic demand, increases the traffic demand to at least its fixed plus assured level, to the moment it is granted the full provisioned assured bandwidth in addition to the fixed bandwidth. The ending moment of the interval is more precisely defined as the start of the first upstream frame in a sequence of K consecutive frames, sufficiently large to average the frame-to-frame variations, over which the average bandwidth allocated to the Alloc-ID meets the specified condition.

Target performance

A few milliseconds is expected (target of 2 ms).

7.4.3 DBA convergence time

This is the worst-case time interval from the moment of a single activity status or traffic load change event at any ONU in a previously stationary system, to the moment the OLT CT adjusts its bandwidth assignments for all the subtending unsaturated ONUs to the levels that are at least equal to the respective fixed plus assured bandwidths, and are within specified bounds (e.g., 20%) of the respective dynamic values computed based on the reference model of clause 7.3. The ending moment of the interval is more precisely defined as the start of the first downstream frame in a sequence of K consecutive frames, sufficiently large to average the frame-to-frame variations, in which the transmitted BWmaps contain bandwidth allocations satisfying the specified condition on average.

Target performance

Ten milliseconds is expected (target of 6 ms).

7.5 Contention-based PON operation

7.5.1 Contention-based allocations

Broadcast, or contention-based allocations (see clause 6.5.2.3) are associated with a specific contention-based function and can be used for upstream transmission by any ONU that meets the appropriate eligibility conditions. Providing Serial Number grants for activating and re-activating the ONUs that are able to transmit at a specific upstream line rate is an example of contention-based allocation which has been fundamental for several generations of standardized PON system. The ONU activation is inherently a contention-based function, because an ONU in the serial number acquisition phase of the activation procedure is lacking the TC layer configuration and cannot be addressed or allocated upstream bandwidth directly.

In addition to using the contention-based allocations for ONU activation, per operator's requirements, an OLT CT in the HSP PON system may optionally choose to use the contention-based allocations for the already activated ONUs that do have a valid TC layer configuration, including the appropriate equalization delay, in the situations when the directed allocations provided individually to such ONUs are likely to remain unanswered or carry idle XGEM frames. The use of contention-based allocations in such situations offers a significant reduction of the overall upstream burst mode overhead and improve the effective upstream throughput.

An eligible ONU responds to a contention-based allocation with a single PLOAM message. The type of the PLOAM message depends on the specific contention-based function.

7.5.2 Contention-based functions

7.5.2.1 ONU activation

ONU activation is a fundamental contention-based function in a PON system. The Alloc-IDs for ONU activation can be either reserved or explicitly assigned. Whether an activation Alloc-ID is reserved or explicitly assigned, it is restricted to a specific upstream line rate or a specific combination of upstream line rates, and is associated with a set of non-rate parameters, including maximum random delay (see clause 13.1.2) and retransmission probability when no collision resolution feedback is received (see clause 7.5.3). The set of reserved broadcast Alloc-IDs is specified in Table 6-2. The non-rate parameters for the reserved Alloc-IDs are well-known and pre-defined as follows: maximum random delay is 48 µs; the retransmission probability is 1.0. The OLT CT may explicitly assign additional broadcast Alloc-IDs for ONU activation (using the broadcast Assign_Alloc-ID PLOAM message) to accommodate the specific rate combinations of interest for the PON infrastructure operator, and to specify the non-rate parameters of the Alloc-IDs for ONU activation function of the specific upstream rates and rate combinations.

An eligible ONU responds to an ONU activation allocation with a Serial_Number_ONU PLOAM message.

If upon issuing an allocation to an ONU activation Alloc-ID, the OLT CT receives a successful transmission from an ONU within the corresponding allocation interval, it performs an ONU-ID assignment to that ONU and proceeds with its activation.

If upon issuing an allocation to an ONU activation Alloc-ID, the OLT CT detects a collision within the corresponding allocation interval, it engages in the set-splitting collision resolution procedure, as specified in clause 7.5.3.

7.5.2.2 Wavelength protection

The OLT CT in a TWDM system can be designated as a protection OLT CT for one or more ONUs hosted by a different OLT CT. Rather than providing directed allocations to all protected ONUs, which are necessarily lost until an actual protection switching event occurs, the OLT CT may withhold the directed allocations and provide a contention-based allocation which any protected ONU upon a protection switching event can use to signal its presence in the wavelength channel.

Wavelength protection Alloc-ID is necessarily pre-ranged. An eligible ONU responds to a wavelength protection allocation with a Tuning_Response(Complete_u) PLOAM message.

The OLT CT is expected to provide frequent allocations to the wavelength protection Alloc-ID.

If upon issuing an allocation to the wavelength protection Alloc-ID, the OLT CT receives a successful transmission from a protected ONU within the corresponding allocation interval, it restores the directed allocations to that ONU in the shortest possible time.

If upon issuing an allocation to the wavelength protection Alloc-ID, the OLT CT detects a collision in the corresponding allocation interval, it restores the directed allocations to all protected ONUs in the shortest possible time, and subsequently may withhold the directed allocations again, once the collision is resolved and all protected ONUs requiring service in the protection channel receive their directed allocations.

7.5.2.3 ONU idle support

The OLT CT may withhold directed allocations to one or more data Alloc-IDs within a subtending ONU as long as said Alloc-IDs are deemed temporarily inactive; that is, lacking the user data to transmit upstream, as can be inferred by the OLT CT through Traffic Monitoring and/or Status Reporting.

Idle support Alloc-ID is necessarily pre-ranged. An eligible ONU responds to an idle support allocation with an Acknowledgement PLOAM message specifying the affected Alloc-ID.

The OLT CT is expected to provide frequent allocations to the idle support Alloc-ID.

If upon issuing an allocation to the idle support Alloc-ID, the OLT CT receives a successful transmission from an ONU within the corresponding allocation interval, it restores the directed allocations to the specified Alloc-ID(s) in the shortest possible time.

If upon issuing an allocation to the idle support Alloc-ID, the OLT CT detects a collision in the corresponding allocation interval, it restores the directed allocations to all affected ONUs in the shortest possible time, and subsequently may withhold the directed allocations again, once the collision is resolved and all newly active ONUs receive their directed allocations.

7.5.2.4 Watchful sleep support

To reduce power consumption, an ONU in a PON system may with OLT CT's consent exercise the watchful sleep power management mode, whereby it is not required to respond to each directed allocation. Consequently, the OLT CT may withhold the directed allocations and provide a contention-based allocation which any ONU that has received a Local Wakeup indication and is willing to terminate the watchful sleep behaviour can use.

Watchful sleep support Alloc-ID is necessarily pre-ranged. An eligible ONU responds to a watchful sleep support allocation with a Sleep_Request (Awake) PLOAM message.

The OLT CT is expected to provide frequent allocations to the watchful sleep support Alloc-ID.

If upon issuing an allocation to the watchful sleep support Alloc-ID, the OLT CT receives a successful transmission from an ONU within the corresponding allocation interval, it restores the directed allocations to that ONU in the shortest possible time.

If upon issuing an allocation to the watchful sleep support Alloc-ID, the OLT CT detects a collision in the corresponding allocation interval, it restores the directed allocations to all ONUs presently exercising the watchful sleep mode in the shortest possible time, and subsequently may withhold the directed allocations again, once the collision is resolved and all ONUs that wish to terminate the low power behaviour are given opportunity to do so.

Table 7-1 – Contention-based functions

Contention-based function ID	Contention-based function	Contention-based function Parameters	Conditions on the ONU to use the contention-based allocation
0x01	ONU activation	Octet 1: Upstream rate in a form of a bitmap, where the LSB corresponds to the nominal line rate $\rho_0 \phi_0$, the following bit, to the nominal line rate $\rho_0 \phi_1$, etc. Octet 2: Maximum random delay in the form of an unsigned integer representing the value in microseconds. Octet 3: Probability *p* used in the set-splitting CRP in the form of an unsigned integer representing the numerator *N* of the fraction $p = N/256$. If left at 0x00, the ONU interprets it as an instruction to apply the default of $p = 0.5$. Octets 4..8: Reserved, set to 0x00.	An ONU operating at the specified upstream line rate while in state O2-3, that is, executing the serial number discovery/ONU-ID assignment phase of the activation procedure.
0x02	Wavelength protection	Octet 1: Retransmission Timeout in the form of an unsigned integer, representing the value in PHY frame periods. Octets 2..8: Reserved, set to 0x00.	An ONU in O9 state; that is, upon acquiring downstream synchronization in a protecting wavelength channel to transmit an upstream PLOAM message indicating its presence and which has not responded to another contention based allocation within the specified retransmission timeout interval.
0x03	ONU idle support	Octet 1: Retransmission Timeout in the form of an unsigned integer, representing the value in PHY frame periods. Octets 2..8: Reserved, set to 0x00.	An ONU in O5 state, whose T-CONT has not been given a directed allocation, has traffic to send, and which has not responded to another contention based allocation within the specified retransmission timeout interval.
0x04	Watchful sleep support	Octet 1: Retransmission Timeout in the form of an unsigned integer, representing the value in PHY frame periods. Octets 2..8: Reserved, set to 0x00.	An ONU in O5 state, which has transitioned into the Active_Held power management state upon Local wake-up indication (LWI).

7.5.3 Collision resolution by set-splitting

7.5.3.1 Collision resolution for contention-based allocation

The OLT CT employs contention-based allocations for ONU activation and for certain pre-ranged contention-based functions, such as wavelength protection, ONU idle support, and, possibly, others. Providing an allocation to a contention-based Alloc-ID may result in a collision occurring the corresponding allocation interval. In case of ONU activation, the collision resolution protocol based on set-splitting applies. In case of pre-ranged Alloc-IDs, the OLT CT may choose to mitigate the collision by restoring the directed allocations to some or all of the affected ONUs. The remaining ONUs follow the behaviour specified by the parameters of the respective contention-based function.

7.5.3.2 Set-splitting collision resolution protocol

Upon issuing an allocation to a contention-based Alloc-ID, the OLT CT monitors the allocation interval to determine the outcome of contention-based allocations. The OLT CT should communicate the outcome of contention-based allocations to the ONUs using one or more Assign_ONU-ID/Collision_Feedback PLOAM messages. The OLT CT controls the frequency of contention-based allocations and the timing of the collision feedback reports, subject to the following constraints:

1) The OLT CT forms and transmits downstream the contention-based allocation feedback (in as many messages as necessary) before providing any other allocation to the same contention-based Alloc-ID.

2) After the feedback is transmitted, the allocation should follow no sooner than 50ms.

7.5.3.3 Providing collision outcome

The OLT CT informs the ONUs of the outcome of contention-based allocations using the Assign_ONU-ID/Collision_Feedback PLOAM messages. The message format is specified to address both the ONU activation and the pre-ranged contention-based functions. In case of ONU Activation Alloc-IDs, when a substantial quiet window and delay randomization is involved, it is conceivable that more than a single event occurs within the allocation interval and more than a single ONU-ID is assigned. The OLT CT sends multiple Assign_ONU-ID/Collision_Feedback PLOAM messages to report such outcomes, indicating in all but the very last such message that the sequence of the messages will continue.

The feedback itself is composed of two 2-bit fields. The first two-bit field refers to the selected main event during the contention-based allocation interval, and reports its outcome as either idle, collision, or successful ONU recognition. It may also report that the outcome has not been evaluated. The second two-bit field refers the remainder of the allocation interval (after the selected main event is reported and discarded), and reports its outcome as either idle, collision, or well-formed burst.

7.5.3.4 ONU support of the set-splitting collision resolution protocol

To implement the set-splitting collision resolution protocol, an ONU maintains an instance of virtual stack (i.e., a single integer L that tracks ONU's own level in the stack). The ONU behaviour is expected to follow these rules:

– An ONU that first wishes to transmit a burst using a contention-based allocation enters the stack on the top (setting $L = 1$).

– Only ONUs that are presently on the top of the stack are allowed to transmit (if their $L = 1$).

– Once an ONU uses a contention-based allocation to transmit a burst, it monitors the downstream PLOAM channel for the allocation interval feedback.

– If an ONU which transmits a burst participates in a collision, it executes a random SPLIT: with probability of 0.5 remains on top of the stack, and with probability 0.5 pushes itself one level down.

– Under different conditions, an ONU may either STAY on the current level of the stack, keeping its value of L intact, execute a PUSH, setting $L = L + 1$, or execute a POP, setting $L = L - 1$.

More specifically, the ONU behaviour is controlled by the following transition tables.

Table 7-2 – Set-splitting collision resolution for activation contention-based Alloc-IDs

Activation allocation outcome	Transmitting ONU (L = 1)	Idle ONU (L > 1)
Idle	STAY (engage APL)	POP
Success – this ONU	CRI completed	CRI completed
Success – other ONU(a) – other events not evaluated	STAY	POP
– other events: idle	STAY (engage APL)	POP
– other events: well-formed burst	STAY	STAY
– other events: collision	STAY	STAY
Collision	SPLIT	PUSH
No feedback received	STAY, transmit with probability p (by default, p = 0.5)	POP
NOTES 1 – APL: Autonomous power leveling (if available) NOTES 2 – CRI: Collision resolution interval		

Table 7-3 – Set-splitting collision resolution for pre-ranged contention-based Alloc-IDs

Activation allocation outcome	Transmitting ONU (L = 1)	Idle ONU (L > 1)
Idle	STAY	POP
Success	CRI completed	POP
Collision	SPLIT	PUSH
No feedback received	STAY, transmit with probability p (by default, p = 0.5)	POP
NOTE – For applicability of Table 7-3, see the contention-based function descriptions in clause 7.5.2.		

8 ComTC framing sublayer

This clause specifies the structure of the downstream FS frame and upstream FS burst along with the format of the downstream FS frame header, upstream FS burst header, and upstream FS burst trailer.

8.1 Downstream ComTC framing

The downstream FS frame size depends on the downstream line rate and the FEC on/off status, as shown in the following Table 8-1.

Table 8-1 – Downstream FS frame size

DS nominal line rate (Gbit/s)	$\rho_0 \phi$
DS PHY frame size (bytes)	$\rho_0 \phi \times 15625$
DS FS frame size (bytes)	$\rho_0 \phi \times 15625 - S_{PSBd}/8 - S_P \times \lceil \rho_0 \phi \times 125000/S_C \rceil/8$ (Note)
NOTE – This formula applies in case FEC is on and PSBd is protected by FEC. S_{PSBd} is the length of PSBd field in bits. S_C is the FEC Code word size expressed in bits, S_P is the FEC Parity size expressed in bits. See clause 10.3 for details.	

For 49.7664 Gbit/s nominal line rate, the downstream FEC code is LDPC(17280,14592), which means S_C = 17280 bits and S_P = 2688 bits. S_{PSBd} is 192 bits, the sizes are:

– DS PHY frame size is 777,600 bytes.

– DS FS frame size is 656,616 bytes as FEC is always ON.

The downstream FS frame consists of the downstream FS header and FS payload. The FS payload is formed on the transmit side (OLT CT) and is processed on the receive side (ONU) by the corresponding ComTC service adaptation sublayer entity (see clause 9.1.1 for discussion of FS payload). The downstream FS frame header consists of a fixed size HLend structure and two variable size partitions: the bandwidth map partition (BWmap) and downstream PLOAM partition (PLOAMd).

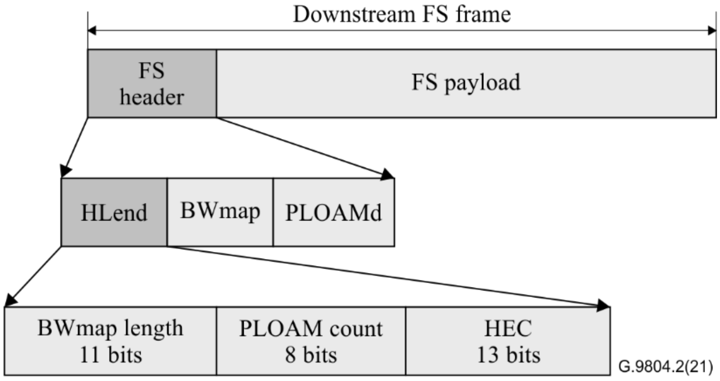


Figure 8-1 – Downstream FS frame format and header fields

8.1.1 HLend structure

HLend is a 4-byte structure that controls the size of the variable length partitions within the downstream FS header. It consists of three fields:

– **BWmap length [11 bits]**: contains an unsigned integer, *N*, indicating the number of allocation structures in the BWmap partition.

– **PLOAM count [8 bits]**: contains an unsigned integer, *P*, indicating the number of PLOAM messages in the PLOAMd partition.

– **Hybrid error correction (HEC) [13 bits]**: an error detection and correction field for the HLend structure, which is a combination of a truncated BCH (63, 12, 2) code operating on the 31 initial bits of the HLend structure and a single parity bit. The details of the HEC construction and verification are specified in Annex A.

8.1.2 BWmap partition

The BWmap is a series of 8-byte allocation structures. The number of allocation structures in BWmap is given in the BWmap length field of the HLend structure. The actual length of the BWmap partition is 8 × *N* bytes.

Each allocation structure specifies a bandwidth allocation to a particular Alloc-ID. A sequence of one or more allocation structures that are associated with the Alloc-IDs that belong to the same ONU and are intended for contiguous upstream transmission form a burst allocation series. The formats of the BWmap partition and an allocation structure are shown in Figure 8-2. The fields of the allocation structure are further explained in the following clauses.

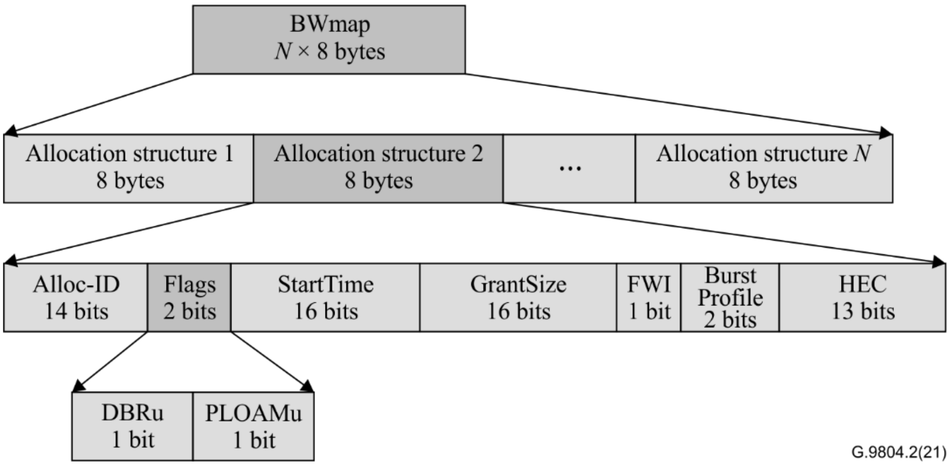


Figure 8-2 – BWmap partition and the format of an allocation structure

8.1.2.1 Alloc-ID field

The allocation ID field contains the 14-bit number that indicates the recipient of the bandwidth allocation, i.e., a particular T-CONT or the upstream OMCC of an ONU. Alloc-ID values and conventions are specified in clause 6.5.2.3.

8.1.2.2 Flags field

The 2-bit Flags field contains two separate indicators:

– DBRu: If this bit is set, the ONU should send the DBRu report for the given Alloc-ID. If the bit is not set, the DBRu report is not transmitted.

– PLOAMu: If this bit is set in the first allocation structure of a burst allocation series (as indicated by StartTime field – see clause 8.1.2.3), the size of the upstream FS burst header should be 52 bytes, and the ONU should transmit a PLOAM message as a part of the FS burst header. If in the first allocation structure of an upstream burst, the PLOAMu bit is not set, the size of the upstream FS burst header should be four bytes, and the PLOAM message should not be transmitted. For all subsequent allocation structures of the same burst, the PLOAMu flag should be set to 0 by the transmitter and ignored by the receiver. See clause 8.2.1 for the details of the upstream FS burst header.

8.1.2.3 StartTime field

The StartTime field contains a 16-bit number that indicates the location of the first byte of the upstream FS burst within the upstream PHY frame. StartTime is measured from the beginning of the upstream PHY frame. It assumes the integer values in the range from 0 to 12149 and refers to 12150 equally spaced time instants within the upstream PHY frame. The interval between two adjacent time instants specified by the consecutive values of StartTime can accommodate a block of length *S* bytes at its corresponding nominal upstream line rate $\rho_0\phi$. *S* is computed as:

$$S = 16 \times \phi \qquad (8\text{-}1)$$

The association of the given value of StartTime with a particular time instant within the upstream PHY frame remains invariant to the ONU's supported line rate.

In each burst allocation series, only the first allocation carries a specific StartTime value. All the remaining allocation structures of the burst allocation series carry the StartTime value of 0xFFFF.

Figure 8-3 illustrates interpretation of StartTime and GrantSize parameters.

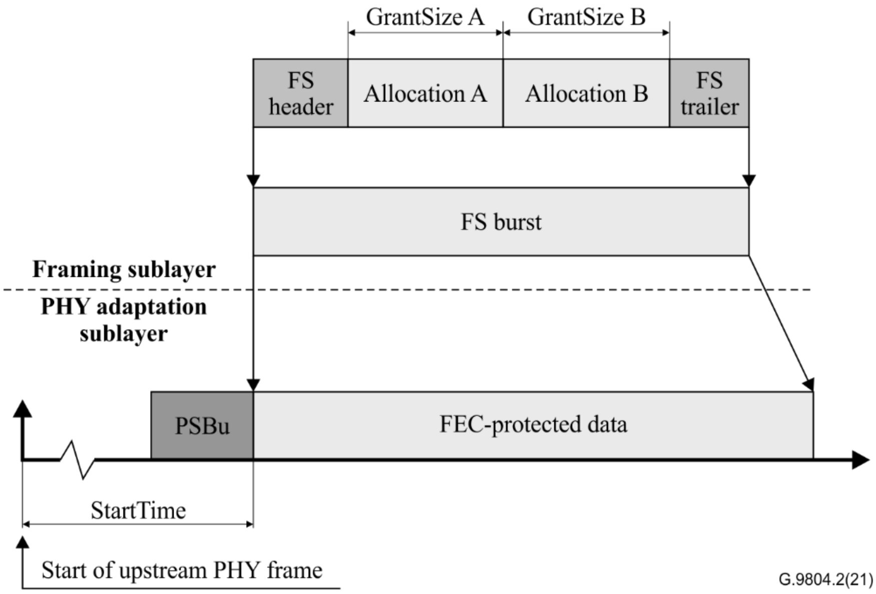


Figure 8-3 – Interpretation of StartTime and GrantSize parameters

Note that the start of upstream PHY frame is just a reference point that is not associated with any externally observable event (unlike the start of the downstream PHY frame which is bound to transmission or receipt of the first bit of the PSync sequence). Note further that the OLT CT and each ONU associate the start of upstream PHY frame with generally different moments in time. See clause 13 for the details of the timing relationships within a wavelength channel.

8.1.2.4 GrantSize field

The GrantSize field contains the 16-bit number that indicates the combined length of the FS payload data with DBRu overhead transmitted within the given allocation. Notably, GrantSize does not include upstream FS header, FS trailer or FEC overhead.

The granularity of the GrantSize field varies with the upstream line rate: for the ONUs transmitting at nominal upstream line rate $\rho_0 \phi$, the granularity of the GrantSize refers to a block of length G bytes, where G is computed as:

$$G = 16 \times \phi \qquad (8\text{-}2)$$

The value of GrantSize is equal to zero for the PLOAM-only grants, including serial number grants and ranging grants used in the process of ONU activation.

The GrantSize of 1 is used for both the DBRu-only transmission (4-byte DBRu field with the rest of the fields filled with idle), and for minimum-size payload allocation.

8.1.2.5 Forced wake-up indication (FWI) bit

When addressing an ONU that supports the protocol-based power management, the OLT CT sets the FWI bit to expedite waking up an ONU that has been saving power. See clause 16 for the details of the ONU power management. When required by the OLT power management state machine, the FWI bit is set in the first allocation structure of each burst allocation series to a given ONU. The value of the FWI bit in the subsequent allocation structures of a burst allocation series is not controlled and is ignored by the ONU.

8.1.2.6 BurstProfile field

The BurstProfile field is a 2-bit field that contains the index of the burst profile to be used by the ComTC PHY adaptation sublayer of the ONU to form the PHY burst. This index refers to the set of valid burst profiles that is communicated to the ONUs by the broadcast or unicast transmissions over the PLOAM messaging channel. For each specified burst profile, the index is explicitly defined in the Burst_Profile PLOAM message (see clause 11.3.3.1).

In each burst allocation series, only the first allocation carries a specific BurstProfile field. The BurstProfile field of the remaining allocation structures in the burst allocation series is ignored by the ONU.

8.1.2.7 HEC field

The error detection and correction field for the allocation structure is a combination of a BCH(63, 12, 2) code operating on the 63 initial bits of the allocation structure and a single parity bit. The details of the HEC construction and verification are specified in Annex A.

8.1.3 BWmap construction and parsing rules

The OLT CT uses BWmap partition to allocate upstream transmission opportunities to the ONUs and the individual Alloc-IDs within each ONU. The frequency and size of allocations to each ONU and each Alloc-ID depend on the respective service parameters and the current power management mode of each given ONU. By design, each BWmap partition may contain at most 2047 allocation structures. There are, however, additional restrictions that the OLT CT should meet while constructing the BWmap in every PHY frame:

1) The OLT CT is required to specify the multiple distinct burst allocation series in the BWmap in the ascending order of their StartTime values.
2) The spacing of adjacent bursts in a BWmap and between the consecutive BWmaps should satisfy the PHY layer requirements detailed in clauses 10.2 and 10.3.2.3.
3) The minimum StartTime value is zero and is invariant to the ONU's upstream line rate. This requirement implies that the PSBu portion of an upstream PHY burst can technically belong to the previous PHY frame.
4) The maximum StartTime value is 12149 and is invariant to the ONU's upstream line rate. This requirement implies that an ONU burst can cross the PHY frame boundary.
5) The maximum number of allocation structures per BWmap is 512.
6) The maximum number of allocation structures per a burst allocation series is 16.
7) The maximum number of allocation structures per given ONU in a BWmap is 64.
8) The maximum number of burst allocation series per given ONU in a BWmap is 16.
9) The maximum GrantSize value of any individual allocation is 12149 (see Note below).
10) The maximum FS burst size, that is, the sizes of all allocations within the burst allocation series together with the FS burst overhead (see Note below) is $\rho_o\phi\times 15625$ bytes at nominal upstream line rate $\rho_o\phi$.
11) The FS burst specification is subject to the constraint, where the GrantSize is summed over all the allocations in the burst allocation series:
    – $\text{StartTime} + \Sigma_n \text{GrantSize}_n \leq \min\,[18225, (\mathbf{2}^{16}\text{-}1)/\phi]$.

NOTE 1 – The largest theoretically possible GrantSize is derived taking into consideration the size of the fixed framing sublayer overhead (a 4-byte header without PLOAMu field and a 4-byte trailer). While FS bursts can cross the nominal PHY frame boundaries, the added constraint imposes a reasonable limit on how far an FS burst defined in one PHY frame can extend into the subsequent PHY frame.

NOTE 2 – In general, the computation of FS burst sizes should take into account any limitations of the ONU PON traffic interface. In general, an ONU will support a certain sustained upstream client rate to the PON interface, as well as an upstream rate adaptation buffer (RAB) size. These parameters are discoverable via the OMCI (see [ITU-T G.988] clause 9.1.18). In order to maintain efficiency, the OLT may need to increase the frequency of grants to an ONU to avoid RAB underflow. If RAB underflow occurs, the ONU will simply send idle frames until the underflow resolves.

Allocating of either consecutive or closely spaced PHY bursts to the same ONU is not a recommended practice. Whenever possible, the OLT CT should allocate for a particular ONU a single burst allocation series instead of closely spaced PHY bursts. The OLT will ensure that the spacing between bursts allocated to the same ONU is greater than the time that would be required for two bursts allocated to the different ONUs plus an extra processing margin of 32/12150th of a 125μs (i.e., $32Q_0$). The ONU shall be capable of responding to grants with this spacing.

Note that the maximum number of burst allocation series per a BWmap is not a relevant design parameter and hence is not mandated here.

In general, the ONU should handle any uncorrectable, errored, or dubious BWmap entries in such a way as to minimize the probability of upstream collision, suppressing transmission whenever necessary. The following specific cases apply:

– If the ONU detects an uncorrectable bit error within an allocation structure, it should suppress transmission for the remainder of the burst.
– If the ONU detects a violation of rule 4 of clause 8.1.3, it should not transmit a burst.
– If the ONU detects a violation of rules 5 to 11 of clause 8.1.3, it should cut the transmission short as if the respective BWmap construction rules were satisfied.
– If the ONU detects that it is allocated two or more consecutive or closely spaced bursts that the ONU cannot properly process, it should not transmit the subsequent burst or bursts.
– If the ONU detects an unknown Alloc-ID within its burst allocation series, it should suppress transmission of the remainder of the burst.
– If the ONU detects its own Alloc-ID within a burst series of another ONU, it should ignore the condition and should not attempt to transmit.

8.1.4 PLOAMd partition

The PLOAMd partition contains zero, one or more PLOAM messages. The length of each PLOAM message is 48 bytes. The number of PLOAM messages in the PLOAMd partition is given by the PLOAM count field of the HLend structure. The actual length of the PLOAMd partition is $48 \times P$ bytes.

The PLOAM message format and the constraints on the PLOAM messaging channel are specified in clause 11. Figure 8-4 illustrates downstream PLOAM partition.

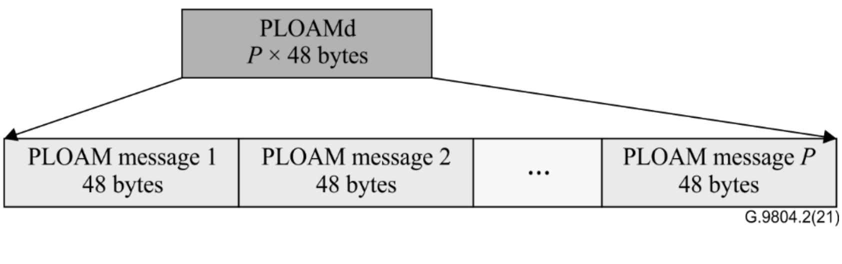


Figure 8-4 – Downstream PLOAM partition

8.2 Upstream ComTC framing

In the upstream direction, the interface between the ComTC framing sublayer and the ComTC PHY adaptation sublayer is represented by an upstream FS burst. The upstream FS burst transmitted by a given ONU has a dynamically determined size and consists of the upstream FS burst header, one or more bandwidth allocation intervals, each being associated with a specific Alloc-ID, and the FS trailer, as shown in Figure 8-5. The size of each allocation interval is dictated by a specific allocation structure of the BWmap.

Each bandwidth allocation interval contains the FS payload section and may contain the allocation overhead that precedes the FS payload. The FS payload is formed on the transmit side (ONU) and is processed on the receive side (OLT CT) by the corresponding ComTC service adaptation sublayer entity (see clause 9.1.1 for discussion of FS payload).

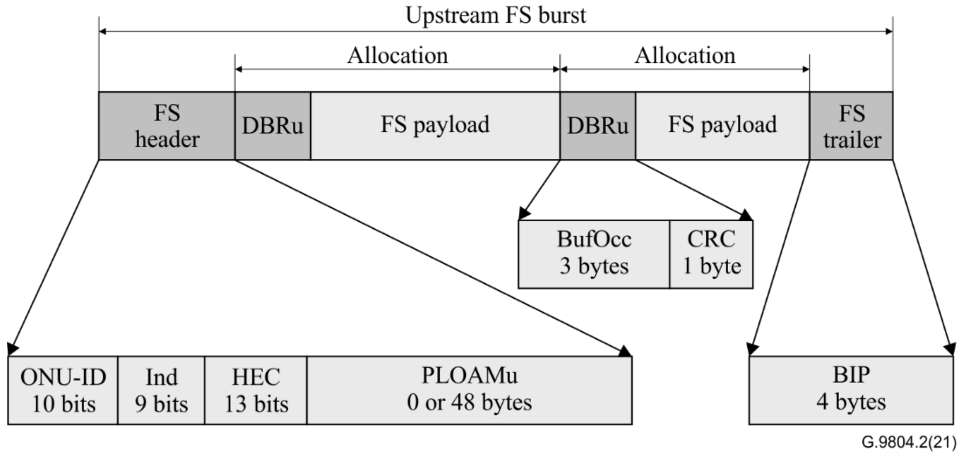


Figure 8-5 – Upstream FS burst format and overhead fields

8.2.1 Upstream FS header

The upstream FS header includes a 4-byte fixed section and a non-fixed section. The fixed section consists of ONU-ID, Ind, and HEC. The non-fixed section has either zero byte or a 48-byte PLOAM message, depending on the value of the PLOAMu flag of the corresponding BWmap allocation structure.

8.2.1.1 ONU-ID field

The ONU-ID field is a 10-bit field that contains the unique ONU-ID of the ONU that is transmitting the burst. The ONU-ID is assigned to the ONU during activation. The OLT can check this field against the BWmap in effect to confirm that the correct ONU is transmitting.

If the ONU which has not been assigned ONU-ID responds to a serial number (SN) grant in order to announce its presence on the PON, it shall use the unassigned value 0x03FF in place of the ONU-ID in the FS burst header (see clause 6.5.2.2 for discussion of ONU identifier).

8.2.1.2 Ind field

The Ind field has nine bits that provide fast unsolicited signalling of the ONU status and are allocated as follows.

– **Bit 8 (MSB): PLOAM queue status**: When set, this bit provides an indication that the ONU's queue of pending upstream PLOAM messages remains non-empty after the current burst is transmitted. If this bit is not set, no additional upstream PLOAMu messages are awaiting transmission.

– **Bits 7 – 2**: Reserved.

– **Bit 1: Cross Alloc-ID busy indication**: If set to 1, provide an indication to the OLT that one or more Alloc-IDs of the ONU which have previously remained idle, now have traffic to be transmitted upstream. If the OLT has withdrawn the directed allocations to idle Alloc-IDs in favor of contention-based idle support Alloc-ID, this bit prompts the OLT to restore directed allocations to all Alloc-IDs of the ONU.
– **Bit 0 (LSB): Dying gasp (DG)**: When this bit is set, it indicates that the ONU has detected a local condition that may prevent the ONU from responding to upstream bandwidth allocations. This indication may assist the OLT in distinguishing fibre plant problems from premises issues. Sending a DG indication does not necessarily constitute a commitment or intent on the part of ONU to cease transmitting. If the condition that has led to DG indication does not persist, the ONU revokes the indication and continues operation. The OLT should not interpret the DG indication by itself as the grounds to withdraw bandwidth allocations to the given ONU.

8.2.1.3 HEC field

The error detection and correction field for the upstream FS header is a combination of a truncated BCH(63, 12, 2) code operating on the 31 initial bits of the header and a single parity bit. The details of the HEC construction and verification are specified in Annex A.

8.2.1.4 Upstream PLOAM (PLOAMu) field

If present, the PLOAMu field contains exactly one PLOAM message. The presence of the PLOAM message is controlled by the OLT CT with the PLOAMu flag of the first allocation structure in the burst allocation series. The PLOAM message length is 48 bytes. The PLOAM message format is given in clause 11.

8.2.2 Allocation overhead

If present, the allocation overhead is composed of the DBRu structure. The presence of the DBRu is controlled by the OLT CT with the DBRu flag of the corresponding allocation structure within the BWmap. The 4-byte DBRu structure carries a buffer status report which is associated with a specific Alloc-ID.

8.2.2.1 BufOcc field

The buffer occupancy (BufOcc) field is three bytes long and contains the total amount of SDU traffic, expressed in 16-byte units, aggregated across all the buffers associated with the Alloc-ID to which the given allocation has been provided. If an individual SDU has length of L bytes, its contribution W towards the reported buffer occupancy is computed as:

$$W = \begin{cases} \left\lceil \frac{L}{16} \right\rceil, & if\ L > 32 \\ 2, & if\ 0 < L \leq 32 \end{cases} \qquad (8\text{-}3)$$

The reported value should represent the best available estimate that corresponds to the moment of time when the report is transmitted, that is, to the start of the upstream allocation interval. The reported value should be inclusive of any traffic that may have been scheduled for upstream transmission within this allocation interval.

While the length L of an individual SDU is a natural number, the BufOcc field needs to encode two special values: 0x000000 denotes an empty buffer, and 0xFFFFFF represents an invalid measurement.

8.2.2.2 CRC field

The DBRu structure is protected using a CRC-8, using the same polynomial as in [ITU-T I.432.1] (g(x) = $x^8 + x^2 + x + 1$). Unlike [ITU-T I.432.1]; however, the cyclic redundancy check (CRC) is not exclusive OR'ed with 0x55. The receiver of the DBRu structure implements the error detecting and correcting functions of the CRC-8. If the CRC-8 indicates that an uncorrectable error has occurred, then the information in the DBRu is discarded.

8.2.3 Upstream FS burst trailer

The upstream FS burst trailer contains a 4-byte wide bit-interleaved even parity (BIP) field computed over the entire FS burst. The OLT CT receiver verifies the BIP to estimate the BER on the upstream optical link. Note that the BIP-based BER estimate is applicable only when the FEC is turned off. Whenever upstream FEC is turned on in the PHY adaptation sublayer, the BER estimate should instead be obtained based on the FEC correction results.

9 Encapsulation method

In an HSP system, the SDUs, which include the user data frames and high-level PON management frames (OMCI), are transmitted in the FS payload sections of the downstream FS frames and upstream FS bursts using the XG-PON encapsulation method (XGEM), originally specified in clause 9 of [ITU-T G.987.3]. The XGEM supports SDU fragmentation, encapsulation and delineation, and is applicable in both upstream and downstream directions. This clause specifies the structure of the FS payload section, the format of the XGEM frame header and payload, the XGEM frame delineation principles, as well as the mapping of different service types into XGEM frames.

9.1 XGEM framing

9.1.1 FS payload structure

The FS payload section is carried in the downstream FS frames and upstream FS bursts as shown in Figures 6-1 and 6-2. The size of the FS payload in a given downstream FS frame is equal to the FS frame size less the size of its FS frame header. The size of each FS payload section in a given upstream burst is equal to the size of the respective allocation less the allocation overhead. The FS payload contains one or more XGEM frames (see Figure 9-1).

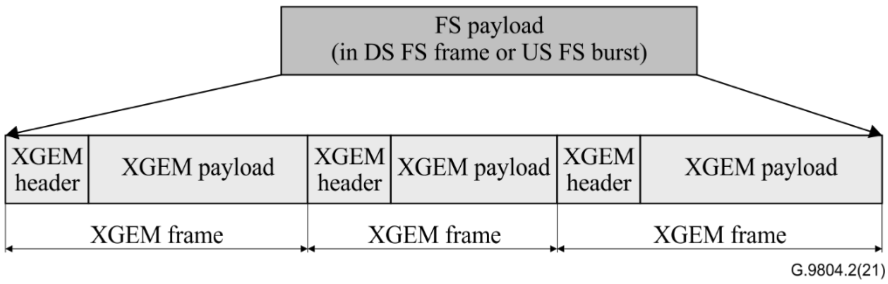


Figure 9-1 – Structure of FS payload

Each XGEM frame contains a fixed size XGEM header and a variable size XGEM payload field.

9.1.2 XGEM frame header

The size of the XGEM header is eight bytes. The format of the XGEM header is shown in Figure 9-2.

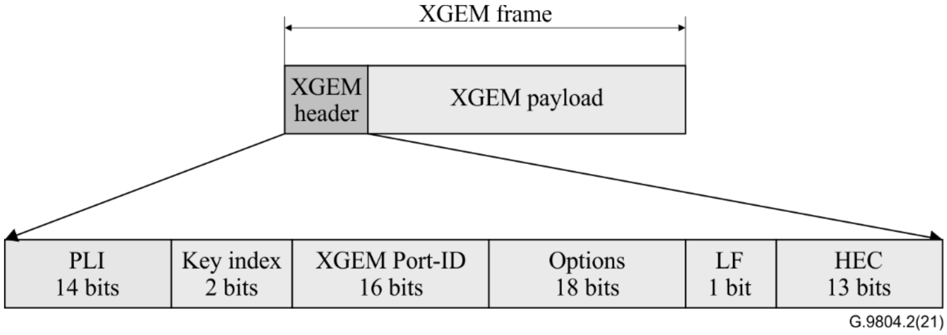


Figure 9-2 – XGEM header format

The XGEM header has the following fields:

– **Payload length indication (PLI)** [14 bits]: The length *L*, in bytes, of an SDU or an SDU fragment in the XGEM payload following the XGEM header. The 14-bit field allows to represent an integer from 0 to 16383, and, therefore, is sufficient to encode the length of an expanded Ethernet frame (up to 2000 bytes) as well as a jumbo Ethernet frame (up to 9000 bytes). The value of the PLI is accurate to a single byte and is not necessarily equal to the size of the XGEM payload which is aligned at the 4-byte word boundaries.

– **Key index** [2 bits]: The indicator of the data encryption key used to encrypt the XGEM payload. Depending on the XGEM Port-ID, the key index refers either to unicast or to broadcast key type. With up to two keys of each type being valid at any given time, the key index value of 01 refers to the first key, while the value of 10 refers to the second key. The value of 00 indicates that the payload is transmitted without encryption; the value of 11 is reserved for future use. If the key index of an XGEM frame contains a reserved value or points to an invalid key (see clause 15.5), the payload of the XGEM frame is discarded.

– **XGEM port-ID** [16 bits]: The identifier of XGEM port to which the frame belongs.

– **Options** [18 bits]: The use of this field remains for future study. The field is set to 0x00000 by the transmitter and ignored by the receiver.

– **Last fragment (LF)** [1 bit]: The last fragment indicator. If the fragment encapsulated into the XGEM frame is the last fragment of an SDU or a complete SDU, the LF bit is set to 1; otherwise, LF bit is 0.

– **Hybrid error correction (HEC)** [13 bits]: The error detection and correction field for the XGEM header, which is a combination of a BCH(63, 12, 2) code operating on the 63 initial bits of the header and a single parity bit. The details of the HEC construction and verification are specified in Annex A.

9.1.3 XGEM payload format

The XGEM payload is a variable-length field controlled by the PLI field of the XGEM header. For a non-idle XGEM frame, the length *P* of the XGEM payload, in bytes, is related to value *L*, transmitted in the PLI field as:

$$P = \begin{cases} 4 * \left\lceil \frac{L}{4} \right\rceil, & \text{if } L \geq 8 \\ 8, & \text{if } 0 < L < 8 \\ 0, & \text{if } L = 0 \end{cases} \tag{9-1}$$

The XGEM payload may contain one to seven bytes of padding at its end. The transmitter fills the padding bytes with 0x55. The padding bytes are discarded by the receiving XGEM engine. Figure 9-3 illustrates the XGEM payload format.

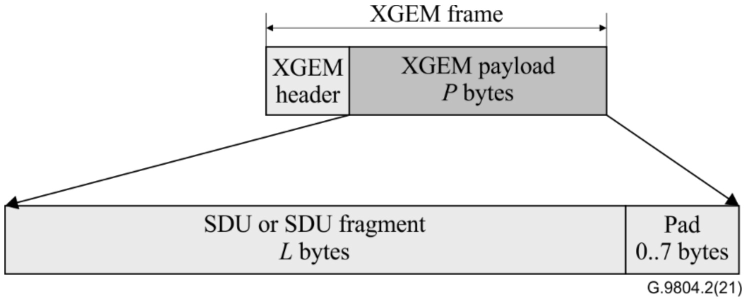


Figure 9-3 – XGEM payload format

9.1.4 Idle XGEM frame

Whenever a transmitter has no SDUs or SDU fragments to send (this includes the case when the SDUs are ineligible for transmission as determined by a non-work-conserving scheduler), or the size of the SDU or SDU fragment exceeds the available FS payload section space but fragmenting it would violate the rules of clause 9.3, the transmitter shall generate Idle XGEM frames to fill the available FS payload section space.

An idle XGEM frame is any XGEM frame with the value of XGEM port-ID equal to 0xFFFF.

The PLI field of an Idle XGEM frame contains the actual size of the frame payload, which may be equal to any multiple of 4, including 0, up to the maximum supported SDU size.

The idle XGEM frames are transmitted unencrypted with Key_Index indicating no encryption and LF = 1. The receiver ignores the Key_Index and LF fields of the header and the payload of the XGEM frame with XGEM port-ID of 0xFFFF.

The XGEM payload content of an idle XGEM frame is formed by the transmitter at its own discretion with the necessary considerations given to the line pattern control and CID prevention. The idle XGEM frame payload is discarded by the receiver.

If the available space at the end of FS payload section is less than the XGEM header size (i.e., is equal to four bytes), the transmitter shall generate a short idle XGEM frame, which is comprised of four all-zero bytes.

9.2 XGEM frame delineation

The delineation process relies upon the presence of a XGEM header at the beginning of every downstream and upstream FS payload section. The receiver, which thus knows the location of the first XGEM header, can use the PLI field to determine the size of the XGEM payload and to find the location of the next XGEM header, repeating the procedure for all the subsequent XGEM frames. The receiver checks whether or not an XGEM frame has been delineated correctly by performing HEC verification on the header of the following XGEM frame.

If HEC verification of the supposed XGEM header fails, the receiver should discard the current XGEM frame along with the remainder of the FS payload, or it can try to hunt for the next XGEM header in the allowed 4-byte aligned locations.

9.3 SDU fragmentation

SDU fragmentation is a process by which an SDU or an SDU fragment available for transmission in the downstream or the upstream direction can be partitioned in two or more fragments and each SDU fragment be transmitted in a separate XGEM frame, as shown in Figure 9-4.

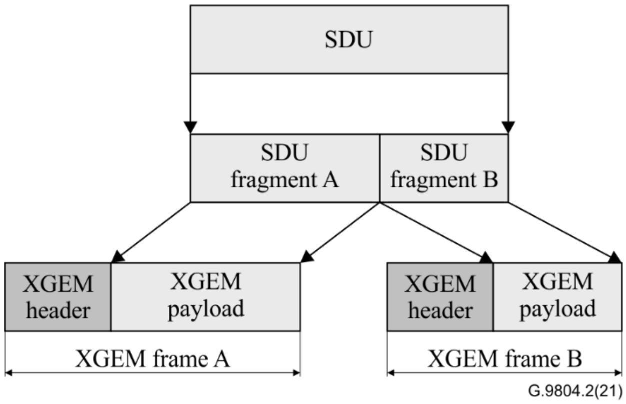


Figure 9-4 – SDU fragmentation

The downstream and upstream fragmentation is subject to the following respective rules.

In the downstream direction, the OLT CT applies fragmentation at its discretion, with an objective that no downstream traffic remains pending after the recipient ONU tunes away to a different TWDM channel. If the available FS payload in the current FS frame is at least 16 bytes, and the length of the SDU available for transmission, including the 8-byte XGEM header, exceeds that available payload, the SDU should be partitioned in two fragments, so that the first SDU fragment completely occupies the available payload of the current FS frame, while the second SDU fragment is transmitted in the FS payload of the next FS frame. Once SDU fragmentation has commenced, the second fragment of the SDU shall be transmitted prior to any other SDU destined to the same ONU; that is, downstream SDU pre-emption between SDUs destined for one ONU is not supported. This ensures that an ONU has to buffer at most one fragmented SDU. An OLT CT may choose to transmit the second fragment of the SDU prior to any other SDU, so that it only has to store at most one fragmented SDU at any given time.

In the upstream direction, an ONU in the Associated substate of the Operation state (O5) applies fragmentation to either new or previously fragmented SDUs without additional restrictions. In the Pending substate of the Operation state (O5), an ONU applies fragmentation to previously fragmented SDUs only, while fragmenting the new (previously unfragmented) SDUs is prohibited. If the available FS payload in the current allocation is at least 16 bytes, and the length of the SDU or the SDU fragment scheduled for transmission, including the 8-byte XGEM header, exceeds that available payload the SDU should be partitioned in two fragments, so that the first SDU fragment completely occupies the available FS payload in the current allocation, while the remainder of the SDU is transmitted in the FS payload of the next upstream allocation associated with the same Alloc-ID, being the subject to the same fragmentation rules. Once SDU fragmentation has commenced, all fragments of the SDU shall be transmitted prior to any other SDU associated with the same Alloc-ID; that is, upstream SDU pre-emption within a given Alloc-ID is not supported.

The following additional rules apply to both the downstream and upstream directions:

– If as a result of fragmentation, the second SDU fragment is less than eight bytes, it should be padded to the minimum of eight bytes to meet the minimum XGEM frame size of 16 bytes.
– If the length of the SDU or SDU fragment available for transmission plus the 8-byte XGEM header, is equal to or less than the available FS payload space, further fragmentation should be avoided by tranmitting the entire available SDU or SDU fragment in the current FS payload.
– If the size of the available FS payload is less than 16 bytes, it should be filled with an idle XGEM frame.

9.4 Mapping of services into XGEM frames

This clause contains the most common cases of service mappings into XGEM frames, that is, Ethernet and multi-protocol label switching (MPLS). It is also applicable to the services that are carried over Ethernet or MPLS (see Table 7-1 of [ITU-T G.989.1]). Any other services are for future study.

9.4.1 Ethernet over XGEM

Ethernet frames are carried directly in the XGEM frame payload. The Ethernet packet's preamble and start frame delimiter (SFD) bytes [b-IEEE 802.3] are discarded prior to XGEM encapsulation. Each Ethernet frame is mapped into a single XGEM frame, as shown in Figure 9-5, or into multiple XGEM frames. In the latter case, the fragmentation rules of clause 9.3 apply. An XGEM frame may not encapsulate more than one Ethernet frame.

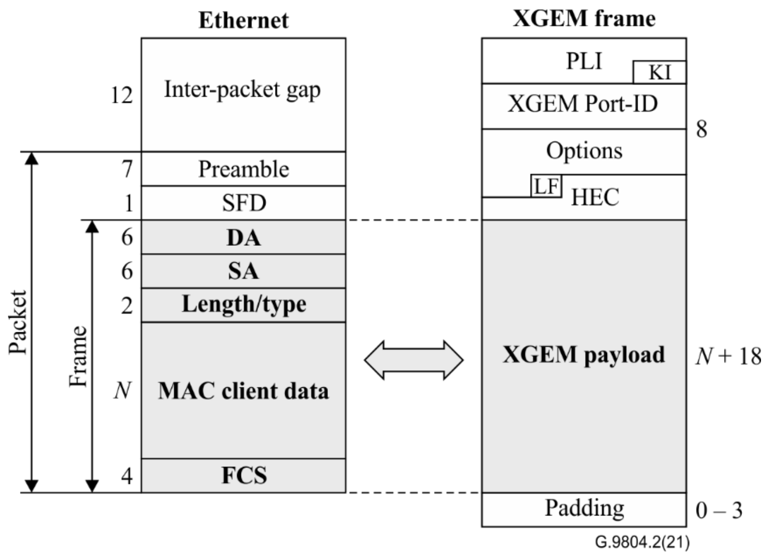


Figure 9-5 – Ethernet mapping into an XGEM frame

9.4.2 MPLS over XGEM

Multi-protocol label switching (MPLS) packets are carried directly in the XGEM frame payload. Each MPLS packet is mapped into a single XGEM frame, as shown in Figure 9-6, or into multiple XGEM frames. In the latter case, the fragmentation rules of clause 9.3 apply. An XGEM frame may not encapsulate more than one MPLS packet.

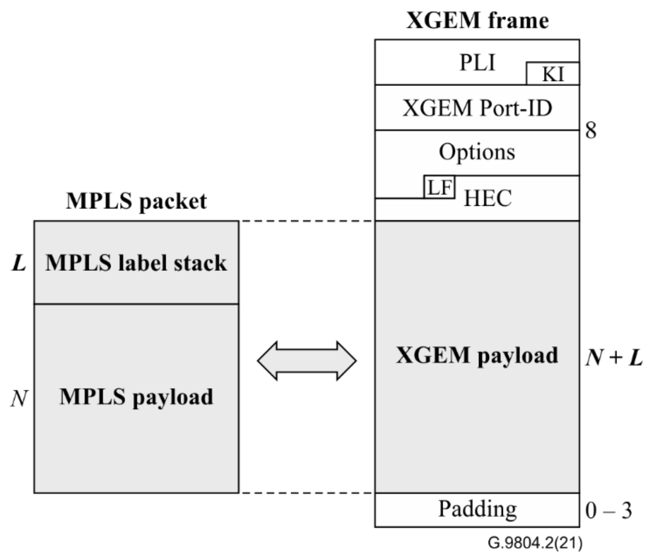


Figure 9-6 – MPLS packet mapping into an XGEM frame

9.4.3 Bonded XGEM

Bonded XGEM frames have the same framing and delineation as non-bonded XGEM frames. The difference is in the way bonded SDUs are mapped to bonded XGEM frames. In general, bonded SDUs are divided into 4-byte words, and the 4-byte words are distributed among the wavelengths participating in bonding and encapsulated in bonded XGEM frames. This is shown as an example in Figure 9-7.

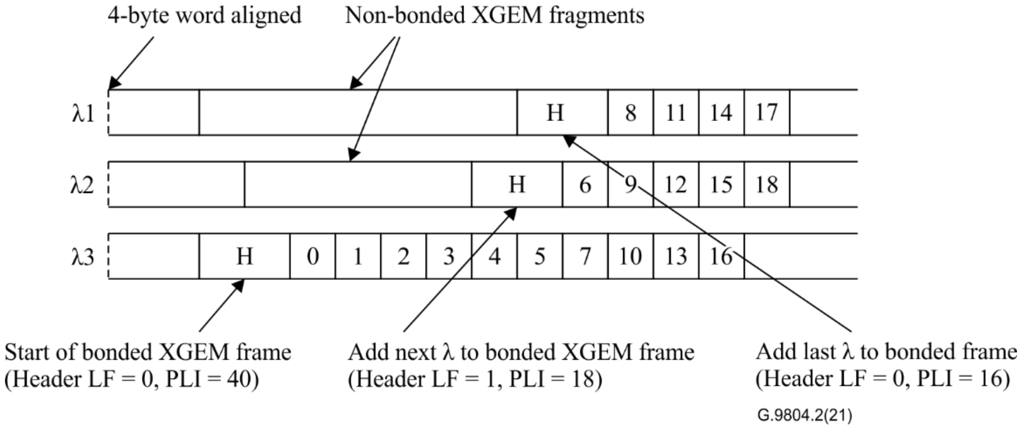


Figure 9-7 – Illustration of bonding principle

In Figure 9-7 there are three wavelengths participating in bonding, with increasing wavelength from λ_1 to λ_3. There can be a mixture of bonded and non-bonded XGEM frames on each wavelength. Any ordinary Port_ID can be configured for bonding via the OMCI, and the receiver can discriminate bonded and non-bonded fragments based upon their Port-ID. A frame to be bonded arrives at the transmitter while there are non-bonded frames being transmitted on λ_1 and λ_2, and to minimize latency the demultiplexing begins initially on λ_3, then adds λ_2 (when it finishes transmitting it's non-bonded frame) and then adds λ_1 (when it finishes transmitting it's non-bonded frame). Note that each sequence of 4-byte words is preceded by an XGEM header, and the numbering of each sequence indicates the multiple of 4 bytes offset from the original SDU. In this case, the original SDU is 74 bytes long, so it is divided into 19 4-byte words (with the last word containing 2 bytes of padding). λ_3 begins transmitting 4-byte offset 0 up to 5. At that point λ_2 and λ_3 alternates 4-byte offsets 6 and 7. Finally, λ_1, λ_2 and λ_3 begin alternating 4-bytes offsets 8, 9, 10 up to 18.

The XGEM header fields operate in the following way. The length specifies the amount of payload contained in that fragment. Thus, the first header has a length of 40 bytes (no padding). The second header has a length of 18 (implicitly indicating 2 bytes of padding). The third header has a length of 16 (no padding). This method relies on the fact that the multiple wavelengths can be precisely aligned in time (that is they have a fixed timing offset known to both the transmitter and receiver), and therefore the transmitter and receiver can agree on the correct ordering of the 4-byte words.

The rules associated with bonded XGEM mapping are as follows:

1) At a given instant in time, if only one wavelength contains a given bonded XGEM frame, then the 4-byte words mapped sequentially to that wavelength, e.g., 4-byte word N, N+1, N+2, are all mapped to that wavelength.

2) At a given instant in time, if two wavelengths simultaneously contain the same bonded XGEM frame, then the 4-byte words alternate between the two wavelengths in order or increasing wavelength, e.g., 4-byte words N, N+2, N+4, are mapped to the lower wavelength, and 4-byte words, e.g., N+1, N+3, N+5, are mapped to the higher wavelength.

3) In general, at a given instant in time, if M wavelengths simultaneously contain the same bonded XGEM frame, the 4-byte words are distributed among the M wavelengths in order of increasing wavelength.

4) While the bonded XGEM frame may appear on any or all of the *M* wavelengths, once a particular wavelength begins transmitting a given XGEM frame, it must continue transmitting on that wavelength until the SDU is complete.

5) A bonded XGEM frame can start on any or all of the *M* wavelengths, and it can start on a different wavelength from frame to frame.

6) When crossing a ComTC frame boundary, any wavelength containing a given bonded XGEM frame at the end of the ComTC frame boundary must continue at the start of the next ComTC frame boundary, assuming there is more data to send in the bonded SDU.

10 ComTC PHY adaptation sublayer

This clause discusses matters of physical synchronization and delineation, forward error correction, scrambling, and optional downstream interleaving for the transmission in ComTC. It reuses the concepts originally specified in [ITU-T G.987.3] and incorporates all the HSP-specific aspects.

10.1 Downstream PHY frame

A working OLT CT is continuously transmitting in the downstream direction. The OLT CT's transmission is partitioned into fixed size downstream PHY frames. The duration of a downstream PHY frame is 125 µs. A downstream PHY frame consists of a physical synchronization block (PSBd) and a PHY frame payload. The PSBd is protected by FEC. The PHY payload is represented by the downstream FS frame whose content is protected by FEC and scrambled.

The start of a particular downstream PHY frame is defined in the context of the given network element and corresponds to transmission (by the OLT CT) or receipt (by the ONU) of the first bit of its PSBd. A diagram of the downstream PHY frame is shown in Figure 10-1.

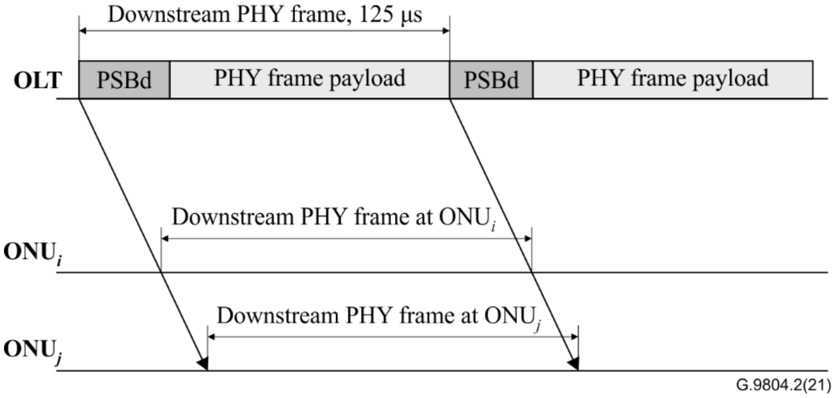


Figure 10-1 – Downstream PHY frame

10.1.1 Downstream physical synchronization block (PSBd)

The downstream physical synchronization block (PSBd) contains three separate structures: PSync, superframe counter (SFC) structure, and operation control (OC) structure (see Figure 10-2).

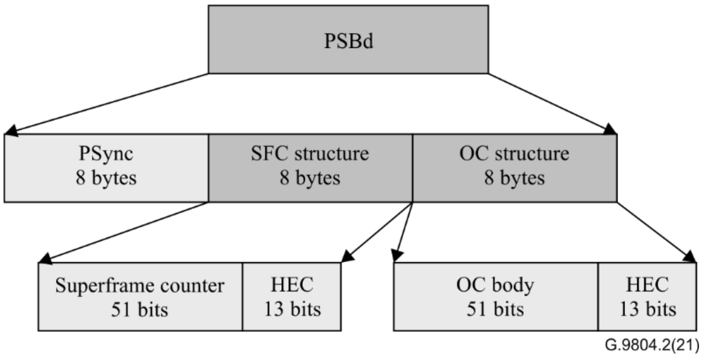


Figure 10-2 – Downstream physical synchronization block (PSBd)

10.1.1.1 Physical synchronization sequence (PSync)

The physical synchronization sequence contains a fixed delimiter pattern. The ONU uses this sequence to achieve alignment at the downstream PHY frame boundary[2].

10.1.1.2 Superframe counter structure

The SFC structure is a 64-bit field that contains a 51-bit superframe counter (SFC) and a 13-bit HEC field (see Figure 10-2). The SFC value in each downstream PHY frame is incremented by one with respect to the previous PHY frame. Whenever the SFC reaches its maximum value (all ones), it is set to 0 on the following downstream PHY frame.

The HEC field is a combination of a BCH(63, 12, 2) code operating on the 63 initial bits of the SFC structure and a single parity bit. The details of the HEC construction and verification are specified in Annex A.

10.1.1.3 Operation control structure

The OC structure contains a 51-bit OC body and a 13-bit HEC field (see Figure 10-2). The HEC field is a combination of a BCH(63, 12, 2) code operating on the 63 initial bits of the OC structure and a single parity bit. The details of the HEC construction and verification are specified in Annex A.

The OC body has the particular format as described below and is filled in by the OLT CT in accordance with explicitly specified data.

At the nominal line rate of 49.7664 Gbit/s in the downstream direction, specific values of the OC body are specified as follows, and shown in Figure 10-3.

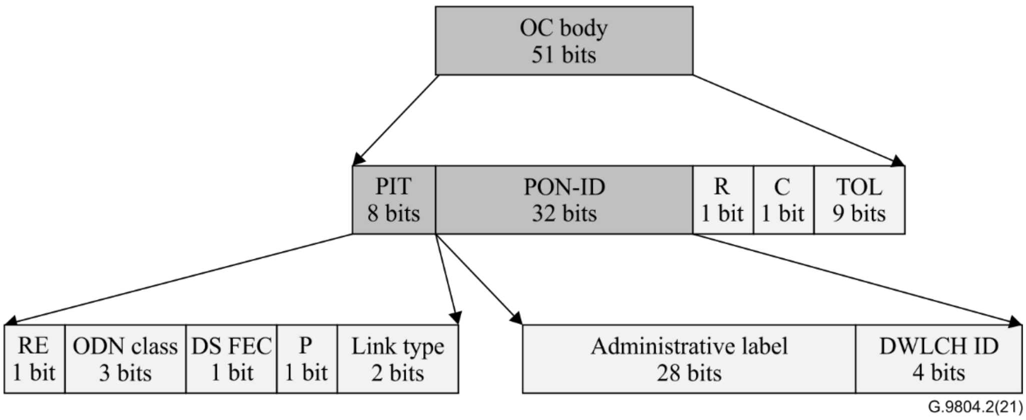


Figure 10-3 – Operation control body

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[2] At the nominal line rate of 49.7664 Gbit/s, the PSync field is 64-bit long and its coding is 0xC5E51840 FD59BB49, and its first two bits are 11.

– **PIT**, or **PON-ID Type** (8 bits, static, provisioned by the operator): an indication of the ODN architecture, the source of the reported launch power and the ODN class. The PON-ID type (PIT) field is further partitioned as follows.
  – **RE flag** (1 bit): indicates whether the transmit optical level (TOL) field contains the launch power of the OLT CT (RE = 0) or of a reach extender (RE = 1).
  – **ODN class** (3 bits): identifies the nominal optical parameters of the transceiver according to ODN optical path loss (OPL) class as defined in the applicable PMD Recommendations. The ODN class encoding for 50G TDM-PON is specified in Table 9-4b in [ITU-T G.9804.3].
  – **DS FEC flag** (1 bit): indicates whether FEC is enabled in the downstream direction. When this bit is set to 1, the FEC of the carried downstream channel is enabled. The DS FEC flag value of 0 is reserved.
  – **P flag** (1 bit): Protocol indication flag indicating TC layer protocol. When this bit is set to 1, the ComTC TC layer protocol is in use. The P flag value of 0 is reserved.
  – **Link type** (2 bits): optical link type as described in the applicable PMD Recommendations.
– **PON-ID** (32 bits, static, provisioned by the operator): identifies the OLT within a certain domain. PON-ID consists of two fields:
  – **Administrative label** (28 bits): supplied by an EMS/OSS to the OLT CT in accordance with certain physical or logical numbering plan. The Administrative Label is treated transparently by the OLT CT.
  – **DWLCH ID** (4 bits): contains an index of the wavelength channel within the ordered set of downstream wavelength channels available in the given PON system (in particular, DWLCH ID has value of 0xF in the case of a TDM system).
– **R** (1 bit): Reserved for future use, set to zero.
– **C** (1 bit): Transmit optical level reference point indicator:
  – C = 0: The TOL value below refers to the S/R-CG reference point (in the case of a TDM system);
  – C = 1: The TOL value below refers to the S/R-CP reference point.
– **TOL** (9 bits, dynamic, maintained by the system): transmit optical level. An indication of the current OLT CT transceiver channel launch power into the ODN (at the reference point indicated by the C bit), if RE = 0, or reach extender transceiver launch power, if RE = 1. Its value is an integer representing a logarithmic power measure having 0.1 dB granularity with respect to −30 dBm (i.e., the value zero represents −30 dBm, 0x12C represents 0 dBm, and 0x1FE represents 21 dBm). The 0x1FF default value indicates that TOL is not supported on the given PON interface.

10.1.2 PSBd field scrambling

After HEC calculation at the transmitter and prior to HEC verification at the receiver, the SFC and OC structures are XOR'ed with the fixed pattern 0x0F0F0F0F 0F0F0F0F. The first bit of the fixed pattern is zero.

10.1.3 ONU downstream synchronization

The OLT CT controls the subtending ONUs by timing their behaviour with respect to the start of the downstream PHY frame, as determined by the respective ONU. To operate on a PON, each ONU must be synchronized with the sequence of the downstream PHY frames. While the details of the synchronization mechanism are internal to the ONU and are not subject to standardization, the following description represents generic properties of a synchronization state machine that is reasonably immune to both false lock and false loss of synchronization (on an independent uniformly random bitstream, under high BER).

The reference ONU downstream synchronization state machine is in Figure 10-4, *false lock* represents the event that an ONU incorrectly goes from Hunt State to Sync State, *correct lock* represents the event that an ONU successfully goes from Hunt State to Sync State, *false loss of synchronization* represents the event that an ONU incorrectly goes from Sync State to Hunt State, and *correct loss of synchronization* represents the event that an ONU correctly goes from Sync State to Hunt State.

The vendor implementation of the ONU synchronization mechanism is expected to meet performance metrics shown in Table 10-1. Note that the performance metrics are guidelines and not meant to be precisely measured. Also note that the equalizer training time is not included in the mean time to correct lock metric.

Table 10-1 – Downstream synchronization performance metrics

Parameter	Value
Mean time to false lock	> 20 years
Mean time to correct lock	< 2 ms
Mean time to false loss of synchronization	> 20 years
Mean time to correct loss of synchronization	< 1 ms
NOTE – In Type B protection (see clause 18.1) the value of mean time to correct lock is <1 ms as the ONU can assume no change in the downstream interleaving mode.	

The ONU begins in the Hunt state, where it considers itself unsynchronized. While in the Hunt state, the ONU searches for the PSync pattern in all possible alignments (both bit and byte) for all possible OLT bit-interleaving modes within the downstream signal. Once the ONU has found the PSync at the beginning of the received PHY frame to a suitable degree of certainty, it transitions into the Pre-Sync state. Note that finding the PSync can include error-tolerant pattern matching and verifying other protocol elements such as the SFC HEC.

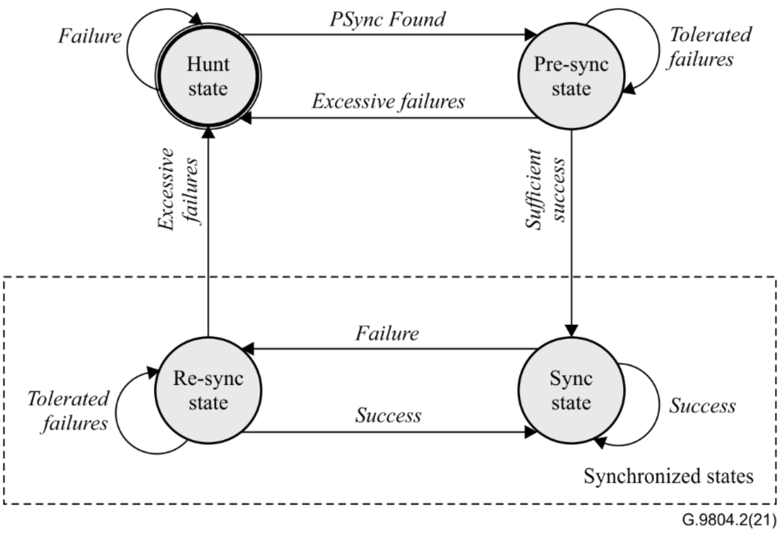


Figure 10-4 – Downstream ONU synchronization state machine

Once in the Pre-Sync state, the ONU still considers itself unsynchronized, awaiting for confirmation. It performs synchronization verification on the following PHY frames. If there is sufficient success in the synchronization verification, then the ONU transitions to the Sync state, whereupon the ONU considers itself synchronized. It returns to the Hunt state if there are excessive failures. Note that the

ONU may persist in the Pre-sync state for some time until it declares sufficient success or excessive failures.

Once in the Sync state, the ONU remains in that state as long as the synchronization verification processes are successful, and transitions into the Re-Sync state if synchronization verification fails.

Once in the Re-Sync state, the ONU is still synchronized, but requires confirmation. The ONU transitions back to Sync state if synchronization verification is successful. However, if there are excessive failures of synchronization verification, the ONU declares loss of downstream synchronization and transitions into the Hunt state.

Appendix X describes possible criteria for the synchronization state machine transitions shown in Figure 10-4 ("PSync found", "Sufficient success", "Tolerated failures", "Excessive failure", etc.). It also provides examples of the ONU synchronization machine, including detection of the downstream interleaving mode set by the OLT CT.

10.1.4 Downstream PHY frame payload

The payload of a downstream PHY frame is obtained from the corresponding downstream FS frame (see clause 8.1) by applying FEC (see clause 10.3), scrambling (see clause 10.4), and, optionally, interleaving (see clause 10.5).

10.2 Upstream PHY frames and upstream PHY bursts

The duration of an upstream PHY frame is 125 μs. As directed by the OLT CT, each ONU determines the point in time corresponding to the start of a particular upstream PHY frame by appropriately offsetting the starting point of the respective downstream PHY frame. The sequence of upstream PHY frame boundary points provides a common timing reference shared by the OLT CT and all the ONUs on the PON, but those points do not correspond to any specific event (unlike the downstream PHY frame boundary points, at which the transmission or receipt of a PSBd starts).

In the upstream direction, upon explicit request by the OLT, each ONU transmits a series of PHY bursts and remains silent, disabling the transmitter, in-between the bursts. An upstream PHY burst consists of an upstream physical synchronization block (PSBu) and a PHY burst payload, the latter representing the upstream FS burst whose content may be protected by FEC and is scrambled. The OLT CT uses the BWmap to control timing and duration of the upstream PHY bursts so that the upstream transmissions by different ONUs are non-overlapping. The upstream PHY bursts of each ONU are referenced to the start of the appropriate upstream PHY frame. An upstream PHY burst belongs to upstream PHY frame N as long as this burst is specified in the BWmap transmitted with downstream PHY frame N. If this is the case, the first byte of the FS burst header is transmitted within the boundaries of PHY frame N. The PSBu portion of an upstream PHY burst may be transmitted within the boundaries of the previous PHY frame. An upstream PHY burst belonging to a particular upstream PHY frame may extend beyond the trailing boundary of that frame.

The relationship between PHY framing boundaries and the upstream PHY bursts of different ONUs is illustrated in Figure 10-5.

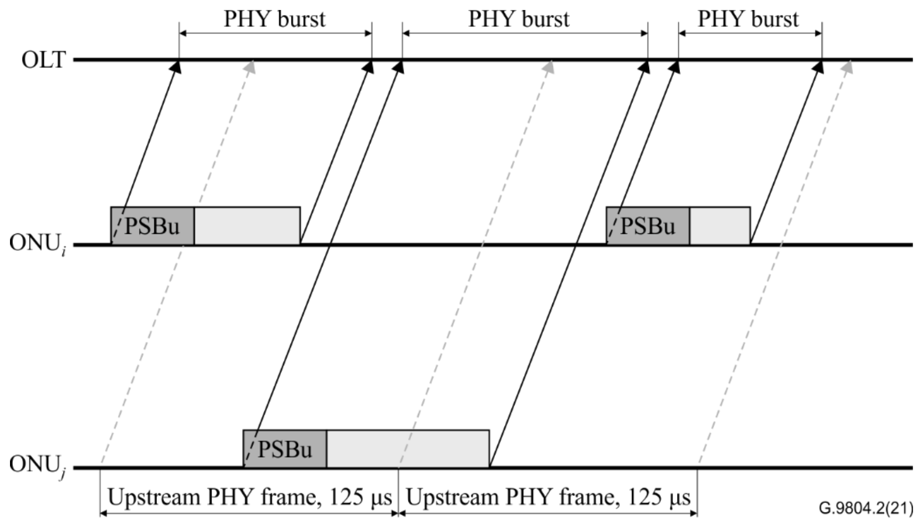


Figure 10-5 – Upstream PHY frame and upstream PHY bursts

10.2.1 Upstream physical synchronization block (PSBu)

The PSBu contains one to four concatenated PSBu segments, each formed by a preamble and a delimiter (see Figure 10-6), which allow the optical receiver of the OLT CT to adjust to the incoming optical signal, thus enabling successful delineation and reception of the PHY burst payload. The preamble and the delimiter of each PSBu segment, as well as the number of PSBu segments and their order is specified by the OLT CT using Burst_Profile PLOAM messages, where one message configures one PSBu segment. The set of parameters needed to configure the entire PSBu constitutes a burst profile, which is identified by a distinct burst profile index. Multiple burst profiles may be concurrently configured on the PON. The set of allowed burst profiles is specified by the OLT CT using Burst_Profile PLOAM messages with distinct burst profile indices. The specific burst profile to be used with a particular PHY burst is selected by the OLT CT by specifying a particular burst profile index in the BurstProfile field of the respective BWmap allocation. See Appendix III for considerations on burst profiles.

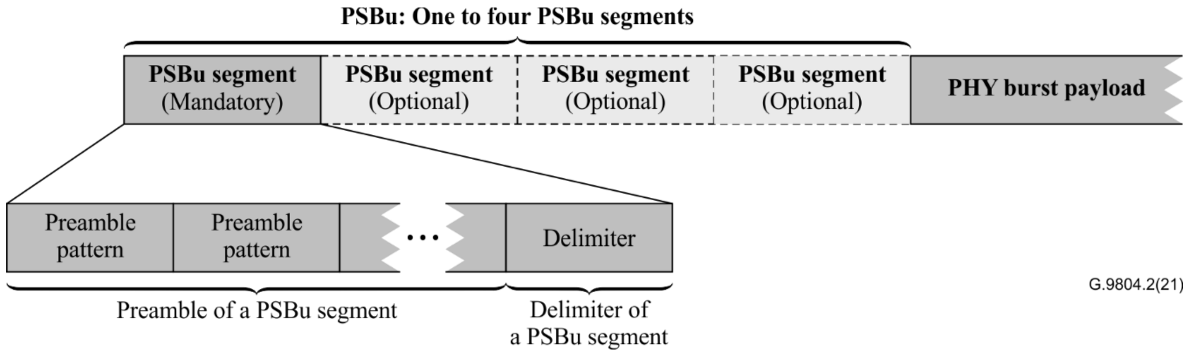


Figure 10-6 – Upstream physical synchronization block (PSBu)

10.2.2 Upstream PHY burst payload

The payload of an upstream PHY burst is obtained from the corresponding upstream FS burst (see clause 8.2) by applying FEC, if so prescribed in the burst profile specified by the OLT CT (clause 10.3.2), and scrambling (clause 10.4.2).

10.2.3 Guard time

To prevent upstream transmissions from colliding and jamming each other, the OLT CT builds the BWmap allowing suitable guard time between upstream bursts from different ONUs. Guard time accommodates the Tx enable and Tx disable times, and includes the margin for the individual ONU transmission drift. The recommended guard time is specified in the applicable PMD Recommendations.

10.3 Forward error correction

The PHY adaptation sublayer employs forward error correction (FEC) to introduce redundancy in the transmitted data. This allows the decoder to detect and correct certain transmission errors. the FEC is based on low-density parity check (LDPC) codes.

Low-density parity check (LDPC) codes are binary codes, which operate on bit symbols and belong to the family of systematic linear block codes. An LDPC code takes a data block of constant size and adds parity bits at the end, thus creating a codeword. Using those parity bits, the FEC decoder processes the data stream, corrects errors and recovers the original data. As their name suggests, LDPC codes are characterized by parity-check matrices that are sparse with mostly 0 elements. A typical LDPC decoder exploits the sparse structure of the parity check matrix in an iterative manner to recover the original data.

This Recommendation employs LDPC codes in a truncated, or shortened and punctured form, thus allowing to work with a more convenient codeword and data block size[3].

FEC support is mandatory for both OLT CT and ONU in the upstream as well as downstream directions. In the downstream direction, FEC is mandatorily on for all ONUs; in the upstream direction, the default FEC mode is on for all ONUs, and turning upstream FEC off is under control of the OLT CT.

10.3.1 Downstream FEC

10.3.1.1 Downstream FEC codeword

The downstream FEC code is represented as Code(S_C, S_D), where S_C is the FEC codeword size in bits and S_D is the data size in bits within a codeword. The parity size in a codeword is represented as S_P, and $S_P = S_C - S_D$. Each downstream PHY frame contains C_D FEC codewords, where:

$$C_D = \lceil \rho_0 \phi \times 125 \times 1000 / S_C \rceil$$

S_{PSBd} is the size of the PSBd field in bits. The data bit size in the last codeword, which may be as long as or shorter than S_D, is represented as S_L. The downstream FEC parity insertion and payload reconstruction are shown in Figure 10-7 and Figure 10-8, respectively. The PSBd is encoded in the first codeword.

3 For example, in the downstream direction and at the nominal line rate of 49.7664 Gbit/s, the FEC code is LDPC(17280, 14592) which is a punctured form of the [b-IEEE 802.3ca] LDPC code matrix.

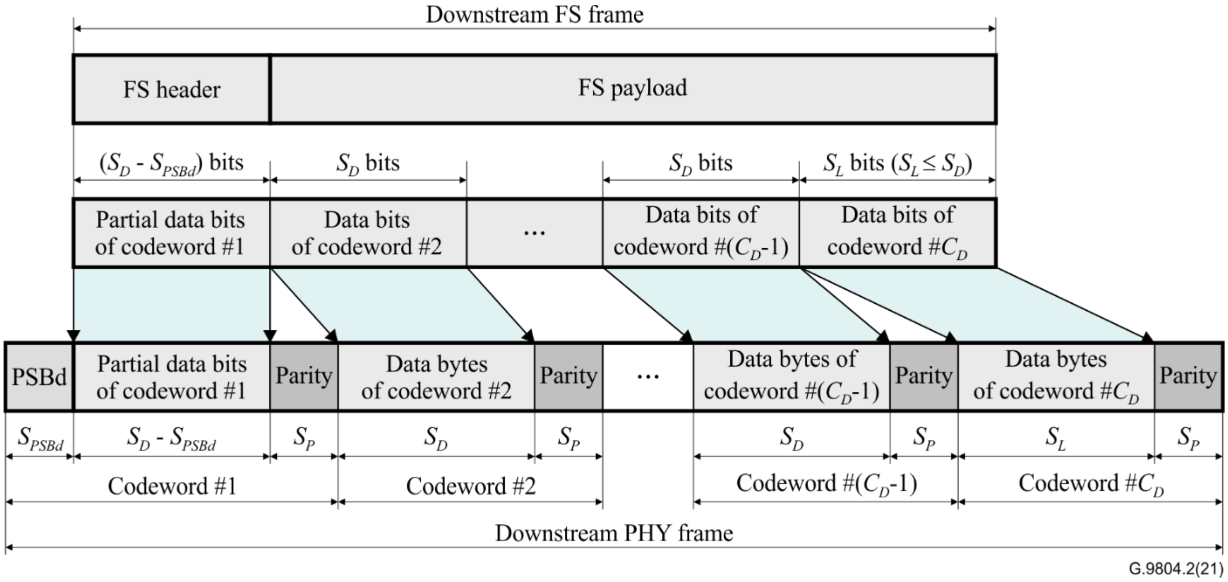


Figure 10-7 – FEC parity insertion in the downstream PHY frame

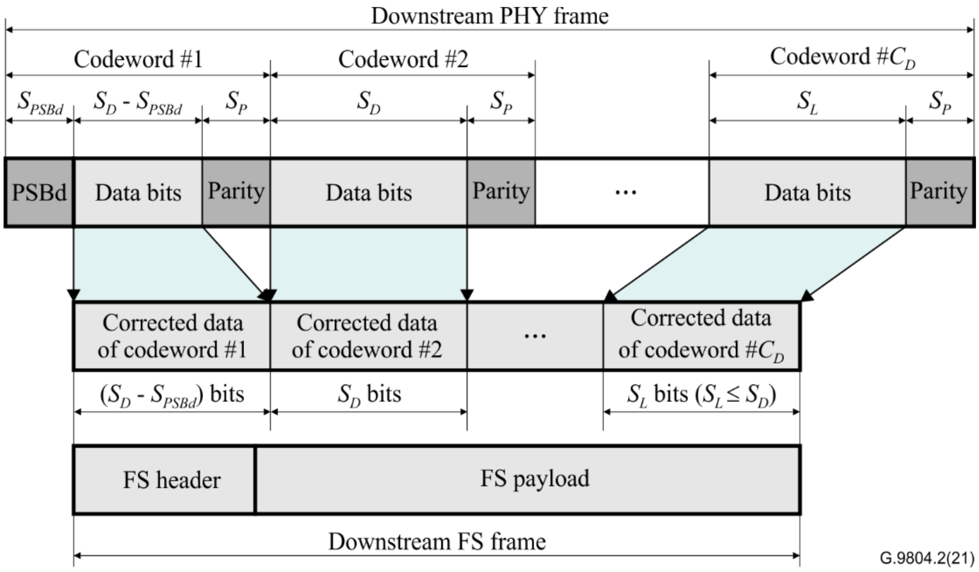


Figure 10-8 – Downstream payload reconstruction at the FEC decoder

For 49.7664 Gbit/s nominal line rate, the downstream FEC code is LDPC(17280, 14592). Each downstream PHY frame contains 360 FEC codewords. Each codeword is 17280 bits long. Within a codeword, 14592 data bits are followed by 2688 parity bits. The LDPC(17280, 14592) code is described in Annex B.1.3. The downstream FEC parity insertion and payload reconstruction for 50G are shown in Figures 10-9 and 10-10, respectively[4].

Note that the downstream FEC encoding processing step is applied before downstream scrambling.

[4] Qualifiers "50G", "25G", and "12.5G" are used as shorthand notations for "49.7664 Gbit/s nominal line rate", "24.8832 Gbit/s nominal line rate", and "12.4416 Gbit/s nominal line rate", respectively.

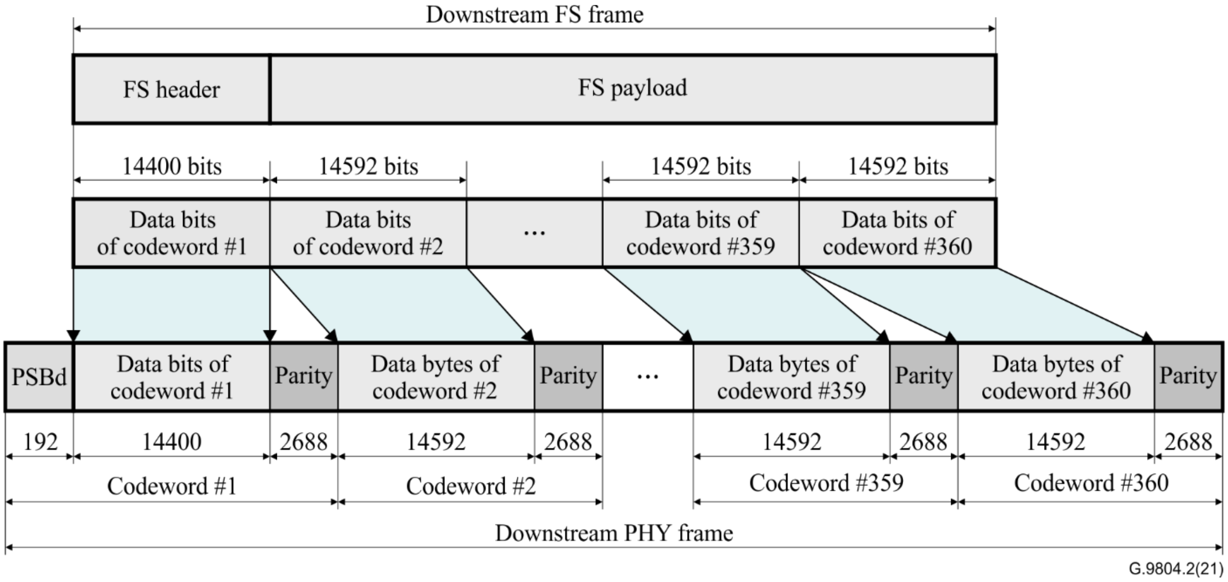


Figure 10-9 – FEC parity insertion in the 50G downstream PHY frame

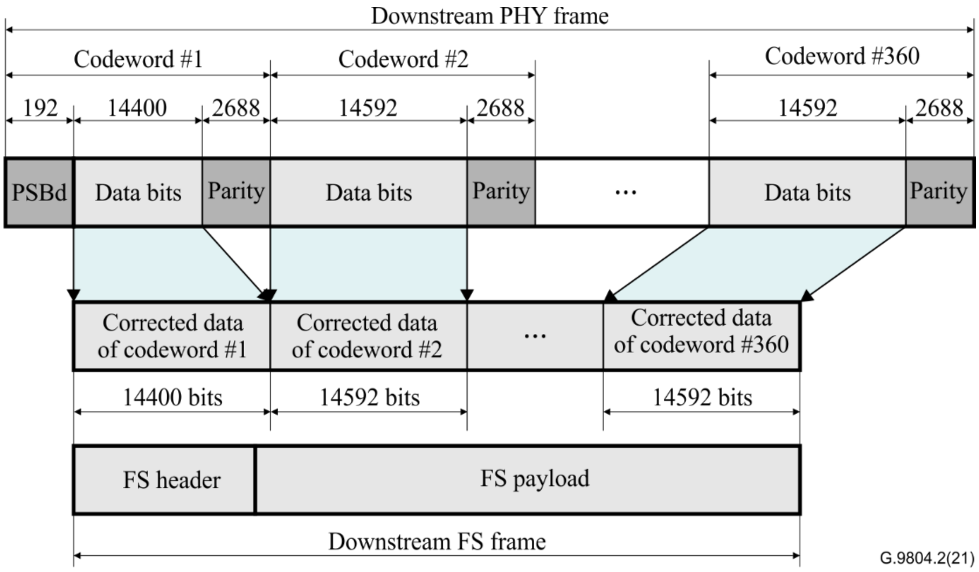


Figure 10-10 – 50G downstream payload reconstruction at the FEC decoder

10.3.1.2 Downstream FEC control

In the downstream direction, FEC is mandatorily on for all ONUs.

10.3.2 Upstream FEC

10.3.2.1 Upstream FEC codeword

In the upstream direction, the PSBu section is not included in the FEC codeword. The first codeword in a PHY burst begins with the upstream FS header section. All allocations of a particular ONU have the same FEC status. Contiguous allocations are encoded as a single block of data, so that there is at most one shortened codeword at the end of the burst. The upstream FEC code is represented as Code(S_C, S_D), where S_C is the FEC codeword size in bits and S_D is the data size in bits within a codeword. The parity size in a codeword is represented as S_P, and $S_P = S_C - S_D$. Each upstream PHY frame contains C_U FEC codewords, where:

$$C_U = \lceil \text{FS\_Burst\_Size} / S_D \rceil$$

The data bit size in the last codeword is represented as S_L. The upstream FEC parity insertion and payload reconstruction are shown in Figures 10-11 and 10-12, respectively.

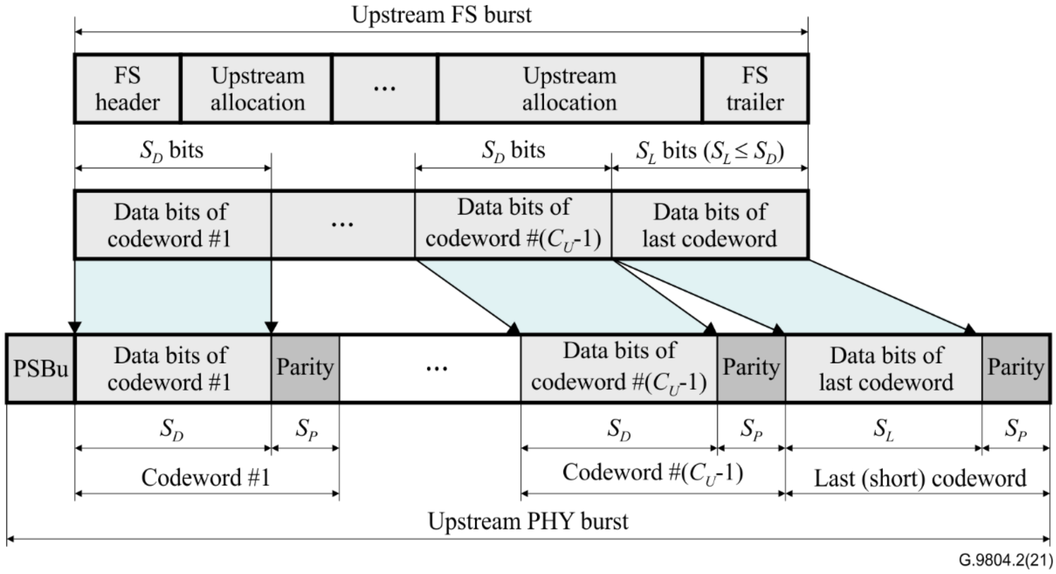


Figure 10-11 – Upstream FEC parity insertion in the PHY frame

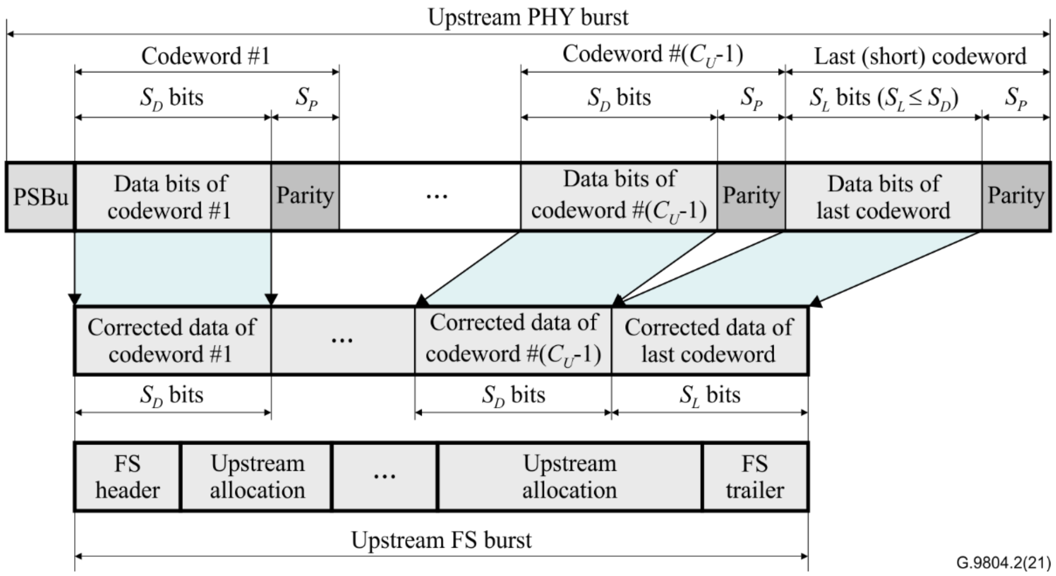


Figure 10-12 – Upstream payload reconstruction at the FEC decoder

For upstream rates of 12.4416 and 24.8832 Gbit/s, the default FEC code is LDPC(17280, 14592), as described in Annex B.1.3. Other optional upstream FEC codes are LDPC codes using the same default mother code matrix but with different amounts of shortening and puncturing, and with codeword lengths bigger than approximately 8700 bits. Implementations may attempt to be configurable so as to enable the support of these future codes. The valid settings for shortening and puncturing are for future study. The default and optional FEC codes for 49.7664 Gbit/s are for future study.

The upstream FEC parity bits insertion and payload reconstruction are shown in Figures 10-13 and 10-14, respectively.

Note that the upstream FEC encoding processing step is applied before upstream scrambling.

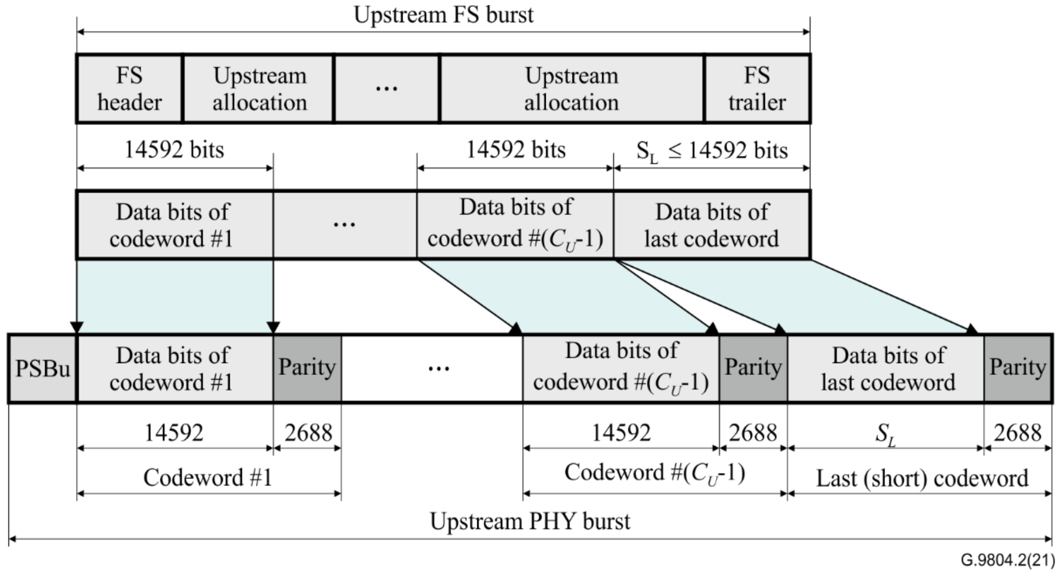


Figure 10-13 – 12.5G/25G Upstream FEC parity insertion in the PHY frame for the default FEC code

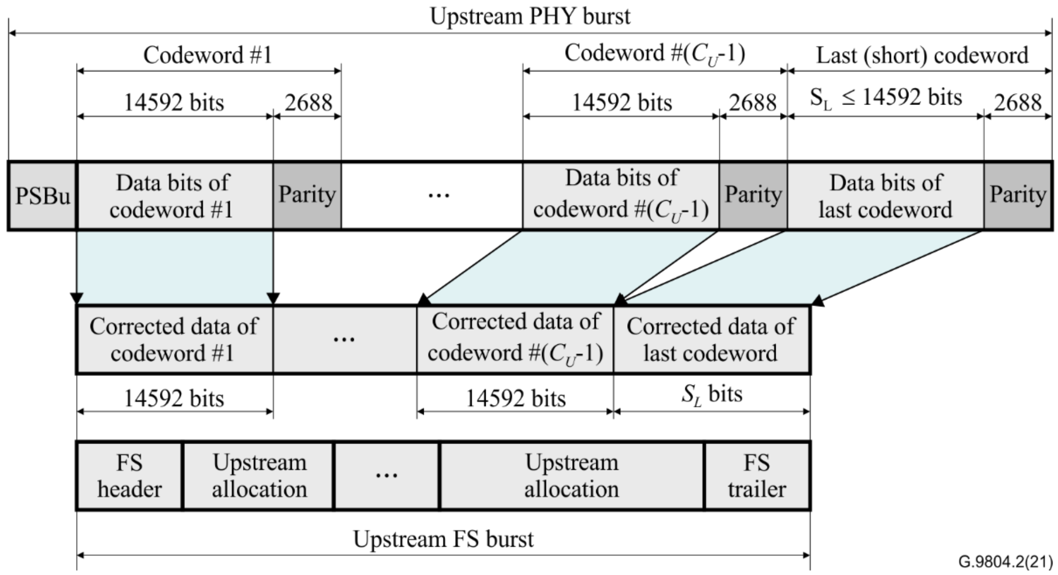


Figure 10-14 – 12.5G/25G Upstream payload reconstruction at the FEC decoder for the default FEC code

10.3.2.2 Upstream shortened last codeword

Whenever an FS burst is not represented by an integer number of S_D -bit data blocks, the FEC encoder generates a shortened last codeword as follows:

– Zero padding bits are added at the end of the last data block to fill it up to S_D bits.

– The parity bits are calculated.

– The padding bits are removed and the shortened codeword is transmitted.

The FEC decoder at the OLT CT conducts the following steps to decode the shortened last codeword:

– The zero padding bits are inserted at the end of data block of the shortened last codeword.

– Following the decoding process, the padding bits are removed.

10.3.2.3 BWmap considerations

When building the BWmap, the OLT CT should take the usage of FEC into account, and strive to provide allocations that will result in an integral number of FEC blocks whenever FEC is utilized.

Once the GrantSizes for the allocations within a FS burst are computed, the OLT CT may calculate the size of the corresponding PHY burst in the following steps:

1) The size of the FS burst is equal to the total of the sum of the GrantSizes, the fixed portion of the upstream FS header, the FS trailer, and the 48-byte PLOAM field if the PLOAMu flag is set.

2) If the requested burst profile has FEC on, the FEC overhead is equal to S_P*C_U bits.

3) Then the total size of the PHY burst is equal to the sum of the FS burst size, the FEC overhead size (if applicable) and the PSBu size. The size of the PSBu is determined by the profile chosen by the OLT CT.

Once the StartTime for the given PHY burst is assigned, the StartTime of the next PHY burst within the BWmap should be spaced by, at least, the sum of the following: the size of the given FS burst with FEC overhead, if applicable, the minimum guard time and the size of the PSBu block of the next PHY burst.

10.3.2.4 Upstream FEC on/off control

The OLT CT dynamically activates or deactivates the FEC encoding functionality for a given ONU in the upstream direction by selecting the appropriate burst profile. When FEC is active, the FEC decoder provides the estimate of the BER on the upstream link. FEC can be turned off, if the observed BER is low enough to trade off between traffic throughput improvement and the effective BER increase. When FEC is deactivated, the BER estimate is obtained using the BIP-32 value in the FS trailer. FEC can be re-activated if the observed BER is too high.

10.4 Scrambling

10.4.1 Scrambling of the downstream PHY frame

The downstream PHY frame is scrambled using a frame-synchronous scrambler. The scrambling polynomial used is $x^{58} + x^{39} + 1$. This pattern is added modulo two to the downstream data. The shift register used to calculate this polynomial is reset by a preload pattern at the first bit following the PSBd block, and is allowed to run until the last bit of the downstream PHY frame.

The preload pattern, which is 58 bits long, changes for every downstream PHY frame. The most significant 51 bits of the preload (P1…P51) are represented by the 51-bit superframe counter transmitted in the PSBd block, so that P51, which is the most significant bit (MSB) of the preload, equals the MSB of the superframe counter. The seven least significant bits of the preload are set to one. A diagram of the downstream and upstream PHY frame scrambling is shown in Figure 10-15. An example of a scrambler sequence is shown in Annex A.

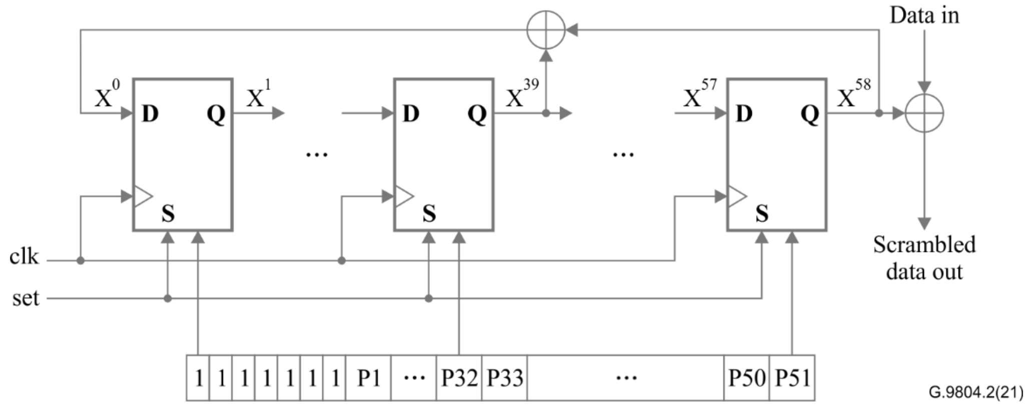


Figure 10-15 – Downstream and upstream PHY frame scrambler

10.4.2 Scrambling of the upstream PHY burst

The upstream PHY burst is scrambled using a burst-synchronous scrambler. The scrambling polynomial used is $x^{58} + x^{39} + 1$. This pattern is added modulo two to the upstream data. The shift register used to calculate this polynomial is reset by a preload pattern at the first bit following the PSBu block, and is allowed to run until the last bit of the PHY burst.

The preload pattern, which is 58 bits long, changes for every upstream PHY frame. If an ONU transits multiple PHY bursts within the same PHY frame, the preload pattern for these bursts remains the same. The most significant 51 bits of the preload (P1…P51) are represented by the 51-bit superframe counter received in the PSBd block of the corresponding downstream PHY frame. The seven least significant bits of the preload are set to 1. A diagram of the upstream PHY burst scrambling is shown in Figure 10-15. An example of a scrambler sequence can be found in Annex A.

10.5 Downstream Interleaving

If interleaving is set to ON (see clause 10.5.2), each downstream PHY frame after scrambling (see clause 10.4.1) shall be interleaved as described below.

If the interleaving is turned off, all bits of the downstream PHY after scrambling are output directly (i.e., the un-interleaved downstream PHY frame is the same as the downstream PHY frame after scrambling).

10.5.1 Interleaving of the donstream PHY frame

For a particular interleaving depth of D and a downstream PHY frame containing N codewords of equal size, where N is a multiple of D, interleaving shall be applied using the following two steps.

Step 1: All the codewords comprising the PHY frame shall be mapped to interleaver blocks, with D codewords in each, such that codewords 1, 2, …, D are mapped to the first interleaver block, codewords (D+1), (D+2),…, 2D are mapped to the second interleaver block, and so on. Codewords (N-D+1)… N-1, and N are mapped to the last (N/D^{th}) interleaver block.

Step 2: The bits of each interleaver blocks shall be arranged as following:

– bits 1, …, S_D of the first codeword are at bit positions 1, D+1, …, $D \times S_D - D + 1$ of the interleaver block;

– bits 1, …, S_D of the second codeword are at bit positions 2, D+2, …, $D \times S_D - D + 2$ of the interleaver block;

– bits 1, …, S_D of the third codeword are at bit positions 3, D+3, …, $D \times S_D - D + 3$ of the interleaver block;

and so on, up to:

– bits 1, …, S_D of the D^{th} codeword are at bit positions D, 2D, …, $D \times S_D$ of the interleaver block.

For 49.7664 Gbit/s downstream nominal line rate, the downstream PHY frame interleaving is optional. When interleaving is set to ON, interleaving depth of D = 4 shall be used. Figure 10-16 shows implementation of the interleaving mechanism for 49.7664 Gbit/s (N=360, D=4).

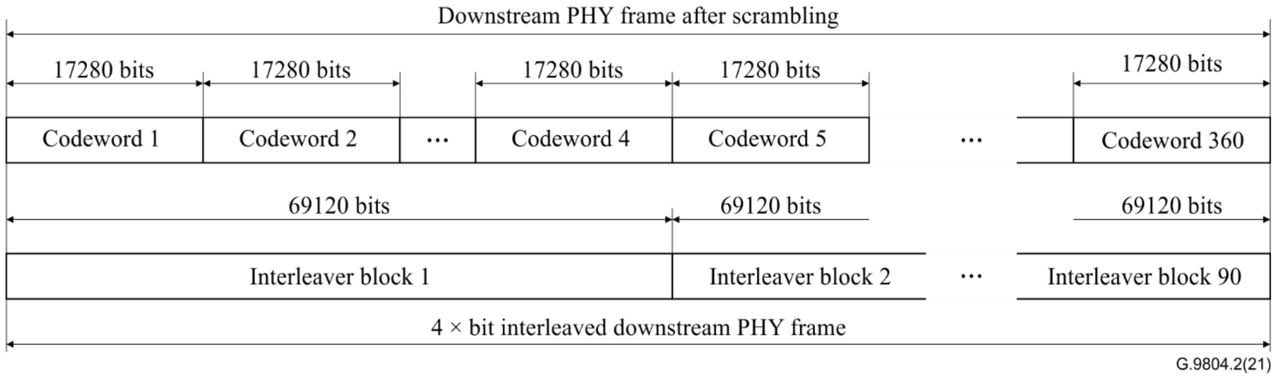


Figure 10-16 – Interleaver blocks in 50G downstream interleaving (*N*=360, *D*=4)

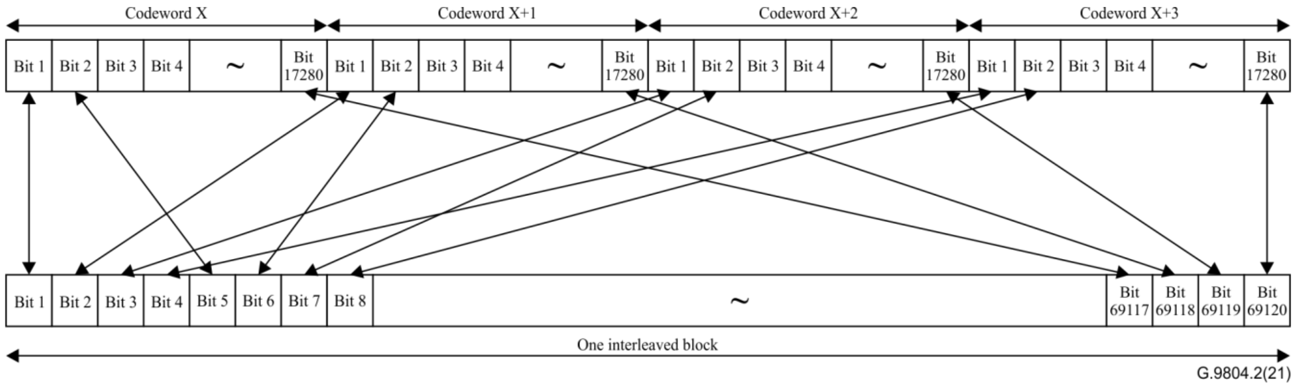


Figure 10-17 – Interleaved bits in 50G downstream interleaving (*N*=360, *D*=4)

10.5.2 Downstream interleaving control

Setting of the interleaver ON or OFF is at the discretion of the OLT. It is a responsibility of the ONU to detect the applied interleaver setting. Some of the options are described in Appendix X.

Note that changing interleaver setting (ON to OFF or OFF to ON) is likely to result in ONU re-synchronization (temporary loss of sync). The time to recover is specified in clause 10.1.3.

Also note that if interleaver is turned off, means to compensate the associated SNR reduction may be needed.

11 PLOAM messaging channel

11.1 Overview

The physical layer OAM (PLOAM) messaging channel is an operations and management facility between OLT CTs and ONUs that is based on a fixed set of 48-byte messages. The PLOAM channel transportation is in-band via the designated PLOAM partition of the downstream FS frame header and the upstream FS burst header. The OLT CT and ONU PLOAM processors appear as clients of the respective ComTC framing sublayers. The PLOAM channel provides more flexible functionality than the embedded management channel and is generally faster than the OMCC.

11.1.1 PLOAM channel functionality

The PLOAM channel supports the following ComTC layer management functions:

– Profile announcement;
– ONU activation;
– ONU registration;
– Encryption key update exchange;
– Protection switching signalling;
– Power management;
– ONU wavelength channel handover signalling;
– ONU wavelength channel bonding.

11.1.2 PLOAM channel rate limitations

Downstream PLOAM messages fall into two categories, the messages that are broadcast to all ONUs and the messages that are unicast to a specific ONU identified by its ONU-ID. Within a given 125-µs frame, the OLT CT may transmit at most one broadcast PLOAM message and at most one unicast PLOAM message to each ONU.

The ONU should be able to store eight unicast and broadcast downstream PLOAM messages before they are processed. The PLOAM processing model is single threaded. The normative processing time of a PLOAM message is 750 µs. That is, once a downstream PLOAM message is received in an empty queue in downstream PHY frame *N*, the ONU should be able to remove the message from the queue, perform all associated processing and generate a response to be sent upstream not later than in upstream PHY frame *N*+6. Furthermore, if at the start of the upstream frame in which a PLOAM response is sent upstream, the PLOAM queue remains not empty, the message at the head of the queue should be processed and the response, if required for the given message type, be prepared for upstream transmission not later than in the 6th subsequent upstream PHY frame.

Note that under these requirements, the OLT CT can determine the maximum number of unacknowledged broadcast and unicast PLOAM messages directed to a given ONU as well as the expected response time for any downstream PLOAM message.

The ONUs transmit upstream PLOAM messages under the control of the OLT CT, which explicitly sets the PLOAMu flag in the respective allocation structures. The OLT CT should grant regular PLOAM transmission opportunities to each ONU. The OLT CT may modulate the rate at which it grants upstream PLOAMu transmission opportunities to the individual ONUs based on the ONU type, provisioned operating and service parameters, number and types of PLOAM messages being transmitted downstream, and the ONU's own feedback in the form of the PLOAM queue status indication.

11.1.3 PLOAM channel robustness

When as a result of unicast PLOAM message processing the ONU enters or remains in the Operation state (O5), it acknowledges the processing outcome by generating an upstream PLOAM message. (See clause 12 for the ONU activation cycle states and transitions.) Such a response PLOAM can be either of a specific type required by the particular PLOAM protocol, or of the general Acknowledgement type. An Acknowledgement PLOAM message is generated also in case of a downstream PLOAM format or processing error. Both a specific type response and the Acknowledgement type response carry the sequence number of the downstream message being acknowledged. In addition, the Acknowledgement type response carries a completion code that indicates the outcome of PLOAM message processing.

Moreover, a PLOAM message of Acknowledgement type is used in response to a PLOAM allocation when no upstream PLOAM is available for transmission. In this case, the completion code allows to distinguish between the idle condition (no PLOAM message in the transmit queue or being processed) and the busy condition (the PLOAM upstream transmit queue is empty, but a downstream PLOAM message is being processed).

Broadcast downstream PLOAM messages that require no response (the Key_Control message requires a response even when it is broadcast) and downstream PLOAM messages that fail the integrity check are not acknowledged.

If the OLT CT expects the ONU to acknowledge or respond to a message, and instead receives merely a keep-alive acknowledgement to a PLOAM request, it can infer that the ONU has failed to process the message. If ONU_i repeatedly fails to acknowledge a downstream PLOAM message, the OLT CT detects the $LOPC_i$ defect.

A ComTC-compliant ONU is expected to react gracefully to any of the PLOAM message types, even if the support of a feature or operation mode corresponding to a specific PLOAM message type has been waived. The graceful reaction implies:

– Upon receipt of a PLOAM message type which does not require Acknowledgement, ignore the message.
– Upon receipt of a PLOAM message type which requires Acknowledgement PLOAM message to be sent upstream, generate an Ackowledgement message with the appropriate Completion_Code.
– Upon receipt of a message type which requires a response in a form of a specific upstream PLOAM message type, generate an appropriate PLOAM message response with the applicable Operation and/or Response codes.

11.1.4 Extensibility

The implementation of the PLOAM channel should be flexible to accommodate future enhancements in a backward-compatible way. While the detailed design is an implementation choice, the remainder of this paragraph provides informative suggestions that are a practical way to permit extensibility. The PLOAM channel termination needs to receive, process, and respond to messages. In some cases, the response needs to come quite quickly (the 750 microseconds above), and some require the triggering of other actions in a timing precise way. In these cases, it may be advantageous to implement these in hardware; however, it is suggested that the hardware can be implemented in a flexible way, with some programmability allowed in the definition of messages and their associated actions. In other cases, there is no significant time urgency to handling of the PLOAM interaction. It is suggested that the PLOAM channel termination function allows for the processing of non-urgent messages in a general purpose processor that is extensible by software upgrade. Furthermore, the PLOAM processing function should anticipate the definition of new messages, and be able to handle such new messages gracefully (e.g., return an error code for an unknown message type).

11.2 PLOAM message format

The PLOAM message structure is shown in Table 11-1, with each field being further defined in the following clauses.

Table 11-1 – Generic PLOAM message structure

Octet	Field	Description
1-2	ONU-ID	Ten bits, aligned at the least significant bit (LSB) end of the 2-byte field. The six most significant bits are reserved, and should be set to 0 by the transmitter and ignored by the receiver.
3	Message type ID	This byte indicates the message type. The enumerated code point for each message type is defined below.

Table 11-1 – Generic PLOAM message structure

Octet	Field	Description
4	SeqNo	Sequence number.
5-40	Message_Content	The message content is defined in the clause that describes each message type ID.
41-48	MIC	Message integrity check.

11.2.1 ONU-ID

The ONU-ID field includes six reserved bits, plus an actual 10-bit ONU identifier that specifies the message recipient in the downstream direction or the message sender in the upstream direction. During ONU activation, the ONU is assigned an ONU-ID in the range from zero to 1019. The reserved ONU-ID value 1023 (0x3FF) indicates a broadcast message in the downstream direction or an ONU that has not been assigned an ONU-ID in the upstream direction. The values 1020 (0x3FC) to 1022 (0x3FE) are reserved and should not appear as ONU-ID in PLOAM messages.

11.2.2 Message type ID

Message type ID is an 8-bit field that indicates the type of the message and defines the semantics of the message payload. Message type ID code points are defined in clause 11.3. Message type ID code points that are not explicitly defined in this Recommendation are reserved. Reserved Message type ID code points should not be allocated by any vendor for any purpose and should not be transmitted in a PLOAM message. Upon receipt of an upstream PLOAM message with an unsupported message type ID, an OLT CT should ignore the message, including the sequence number field. Upon receipt of a downstream PLOAM message with a reserved or unsupported message type ID, an ONU should ignore the message, if it was sent with the broadcast ONU-ID, or negatively acknowledge the message as an unknown message type, if it was sent to that specific ONU-ID.

11.2.3 SeqNo

SeqNo is an 8-bit field containing a sequence number counter that is used to ensure robustness of the PLOAM messaging channel.

In the downstream direction, the SeqNo field is populated with the value of a corresponding OLT CT sequence number counter. The OLT CT maintains a separate sequence number counter for each ONU unicast and for the broadcast PLOAM message flow. The counter for the broadcast PLOAM message flow is initialized to 1 upon OLT CT reboot. For each ONU, the OLT CT initializes the sequence number counter to 1 upon ONU-ID assignment during activation, or upon receipt of the Tuning_Response(Complete_u) PLOAM message during ONU wavelength channel handover. Upon transmission of a broadcast or unicast PLOAM message, the appropriate sequence number counter is incremented. Each sequence number counter rolls over from 255 to 1; the value 0 is not used in the downstream direction.

In the upstream direction, whenever an upstream PLOAM message is a response to a downstream PLOAM message, the content of the SeqNo field is equal to the content of the SeqNo field of the downstream message. The same SeqNo may appear on more than one upstream PLOAM message, for example, for the conveyance of a multi-fragment encryption key. If a PLOAM message is originated autonomously by the ONU, for example, Serial_Number_ONU sent in response to a serial number grant, the value SeqNo = 0 is used. The value SeqNo = 0 is also used in responses to PLOAM grants at times when the ONU has no upstream PLOAM messages enqueued.

In TWDM mode of operation, when the OLT CT in the Expecting state of the OLT wavelength channel handover state machine (see clause 17.3.3) receives a Tuning_Response(Complete_u) PLOAM message, it accepts it as an indication of a successful handover ignoring the SeqNo value.

11.2.4 Message content

Octets five to 40 of the PLOAM message are used for the payload of PLOAM messages. The message payload content is specific to a particular message type ID and is defined in clause 11.3. Unused octets of the message payload content are padded with the value 0x00 by the transmitting PLOAM processor and are ignored by the receiving PLOAM processor.

11.2.5 Message integrity check

The message integrity check (MIC) is an 8-byte field that is used to verify the sender's identity and to prevent a forged PLOAM message attack.

MIC generation is specified in clause 15.6. Key generation and management for PLOAM MIC is specified in clause 15.8.

For the purpose of MIC verification, there is no distinction between the significant octets and padding octets of the message payload content. Using the PLOAM message content and the shared PLOAM integrity key, the sender computes the MIC and transmits it with the PLOAM message. Using the same message content and shared key, the receiver computes its version of the MIC and compares it with the MIC value carried in the received PLOAM message. If the two MIC values are equal, the PLOAM message is valid. Otherwise, the message is declared invalid and should be discarded.

The shared PLOAM integrity key can be either ONU-specific, derived based on the Master session key (MSK) or default (see clauses 15.3.3 and 15.8.1, respectively). The selection of either ONU-specific or default PLOAM integrity keys for each PLOAM message type is specified in clauses 11.3.3 and 11.3.4.

11.2.6 Common elements of PLOAM message format

11.2.6.1 Vendor_ID

Vendor_ID is the first of the two components of the ONU serial number, which ONU reports to the OLT CT in the course of activation or upon handover, and which the OLT CT stores and subsequently uses to address the ONU when the ONU-ID is not yet available or is considered unreliable.

The code set for the Vendor_ID is specified in [ATIS-0300220].

The four characters are mapped into the 4-byte field by taking each ASCII/ANSI character code and concatenating them. For example, Vendor_ID = ABCD fills the four octets of the PLOAM message format element as shown in Table 11-2:

Table 11-2 – An example of filling Vendor_ID = ABCD in a PLOAM message

Character	Octet	Value
A	1	0x41
B	2	0x42
C	3	0x43
D	4	0x44

11.2.6.2 VSSN

Vendor-specific serial number (VSSN) is the second of the two components of the ONU serial number, which ONU reports to the OLT CT in the course of activation or upon handover, and which the OLT CT uses to address the ONU when the ONU-ID is unavailable or unreliable.

VSSN is a four-byte unsigned integer, selected by the ONU vendor.

11.2.6.3 Correlation tag

For the upstream message types that may have to be transmitted multiple times with varying optical power and the frequency (Serial_Number_ONU and Tuning_Response), the ONU generates and inserts the Correlation tag into the transmitted message. Once the upstream PLOAM message is received, the OLT CT copies the correlation tag of the successful upstream PLOAM message into the downstream PLOAM response (Calibration_Request or Adjust_Tx_Wavelength), so that the ONU is able to associate the response with the variable parameters of the successfully transmitted message.

In an upstream PLOAM message, the correlation tag is an ONU-generated non-zero 16-bit field, which should take a different value each time the transmitter optical power or frequency are changed. In a downstream PLOAM message, the correlation tag of all zeros indicates that the message is not sent as a response to an ONU's activation or tuning attempt. An ONU that does not change the transmitter optical power and frequency uses a default value of the Correlation tag equal to 0xFFFF.

11.2.6.4 Calibration record status

The ONU reports its calibration record status in the course of activation or upon handover.

Calibration record status is an 8-octet array which contains a two-bit accuracy indicator for each upstream wavelength channel, which is currently active or potentially present in an HSP system.

The LSB nibble of octets one through eight pertains to even-numbered UWLCH IDs from 0000 to 1110, respectively. The MSB nibble of octets one through eight pertains to odd-numbered UWLCH IDs from 0001 to 1111, respectively. Each individual nibble has a form: 00AA, where AA is an individual calibration accuracy indicator having the following encoding:

– 00: channel unspecified (not announced via Channel_Profile);
– 01: uncalibrated;
– 10: loose;
– 11: sufficient.

In a fixed-wavelength TDM system, the nibble corresponding to the default UWLCH ID of 1111 is set 0011, while the other nibbles are 0000.

11.2.6.5 Tuning granularity

Tuning granularity is one of the two parameters related to the upstream wavelength dithering mechanism (see clause 17.4) which the ONU reports to the OLT CT in the course of activation or upon handover.

It is an 8-bit unsigned integer which represents the tuning granularity of the ONU transmitter expressed in units of 1 GHz.

The value of 0x00 indicates that the ONU does not support fine tuning/dithering.

11.2.6.6 One-step tuning time

One-step tuning time is the second of the two parameters related to the upstream wavelength dithering mechanism (see clause 17.4) which the ONU reports to the OLT CT in the course of activation or upon handover. It is an 8-bit unsigned integer which represents the value of the tuning time for a single granularity step, expressed in units of PHY frames.

The value of 0x00 indicates that the ONU does not support fine tuning/dithering.

11.2.6.7 Attenuation

Attenuation parameter represents a requested attenuation level as a part of the power levelling instruction to an ONU, or an ONU's attenuation level at the time of the message transmission as a part of the power levelling report.

This is a one-octet field of the form 0000 MMMM, where MMMM is the attenuation level:

– 0000: Unattenuated transmission;

– 0001..0111: attenuation level in steps of 3 dB.

Other values reserved (no action).

11.2.6.8 Power levelling capability

Power levelling capability is a seven-bit bitmap of the form 0CCC CCCC, whereby a bit in the *K*-th least significant position indicates that the ONU supports the attenuation level of 3*K* dB. For example, 0000 0010 indicates support of 6 dB attenuation level.

11.3 PLOAM message definitions

11.3.1 Downstream PLOAM message summary

Table 11-3 summarizes the downstream PLOAM messages.

Table 11-3 – Downstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x01	Burst_Profile	Broadcast or unicast message to provide upstream burst header information.	Periodically with programmable periodicity.	The ONU stores the burst profile for use in subsequent upstream transmissions. If in Operation state (O5) and responding to a directed Burst_Profile message, send Acknowledgement.
0x03	Assign_ONU-ID/ Collision_Feedback	To link a free ONU-ID value with the ONU's serial number and/or to report the outcome of a contention-based allocation.	When the OLT CT processes a contention based allocation, including serial number allocations for activation purposes and pre-ranged allocations for specified contention-based functions.	The appropriately identified ONU executes set-splitting collision resolution protocol, and/or sets its ONU-ID and also its default Alloc-ID and OMCC XGEM port-ID. No Acknowledgement.
0x04	Ranging_Time	To indicate the round-trip equalization delay (EqD). As a broadcast message, may be used to offset the EqD of all ONUs (for example, after a protection switching event).	When the OLT CT decides that the delay must be updated. See the ONU activation description in clause 12.	The ONU fills or updates the equalization delay register with this value. If in or transitioning to Operation state (O5) and responding to directed Ranging_Time message, send Acknowledgement.

Table 11-3 – Downstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x05	Deactivate_ ONU-ID	To instruct a specific ONU to stop sending upstream traffic and reset itself. It can also be a broadcast message.	At the implementor's discretion.	The ONU with the specified ONU-ID switches off its laser. The ONU-ID, default and explicit Alloc-IDs, default XGEM Port-ID, burst profiles, and equalization delay are discarded. The ONU transitions to the Initial state (O1). No Acknowledgement.
0x06	Disable_Serial_ Number	Broadcast message to disable/enable a specific ONU or a specific ONU set.	At the implementor's discretion. Note that in a TWDM system, to effectively bring an ONU out of the Emergency Stop state, the Disable_Serial_Numb er PLOAM message with the Enable option must be transmitted in all available TWDM channels	The addressed ONUs (that is, the ONU with the specified serial number, or, the tuned-in ONUs in the Serial Number state (O2-3), or all tuned-in ONUs) switch off the laser and transition to the Emergency Stop state (O7). The disabled ONUs are prohibited from transmitting. Enable option: The addressed ONUs (that is, the ONU with the specified serial number or all tuned-in ONUs in the Emergency Stop state (O7)) transition to the Initial state (O1). The enabled ONUs discard the ComTC layer configuration and restart the activation, as specified in clause 12. No Acknowledgement.
0x09	Request_ Registration	To request an ONU's Registration_ID.	At the implementor's discretion; ONU has been previously activated.	Send the Registration message.

Table 11-3 – Downstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x0A	Assign_Alloc-ID	1. To explicitly assign a specified Alloc-ID to a particular ONU or to a particular contention-based function. 2. To cancel a previously executed Alloc-ID assignment.	As part setting up the PON or individual ONU TC layer configuration. The default Alloc-ID for OMCC need not be explicitly assigned.	If responding to a directed Assign_Alloc-ID message, the ONU acknowledges the message and responds henceforth to bandwidth grants to this Alloc-ID. If responding to a broadcast Assign_Alloc-ID message, the ONU henceforth uses this Alloc-ID for the specified contention-based function.
0x0D	Key_Control	The OLT CT instructs the ONU to generate a new data encryption key of specified length or to confirm an existing data encryption key.	At the implementor's discretion.	Send one Key_Report message for each 32-byte key fragment of response content.
0x12	Sleep_Allow	To enable or disable ONU power saving in real time.	At the implementor's discretion.	If the ONU power management has been enabled using OMCI, the ONU response is controlled by the state machine of clause 16. Otherwise, the ONU ignores the message.
0x13	Calibration_ Request	In TWDM mode of operation, to instruct the ONU to calibrate a specific pair of downstream and upstream wavelength channels. No function in TDM mode of operation.	At the implementor's discretion.	The ONU makes calibration record for the confirmed upstream wavelength channel (see clause 17.2) and follows the further calibration instructions by tuning to the specified pair of downstream and upstream wavelength channels. No Acknowledgement.

Table 11-3 – Downstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x14	Adjust_ Tx_Wavelength	To instruct the ONU to adjust its upstream transmitter wavelength.	As a feedback to an upstream activation or tuning attempt, when an upstream wavelength channel drift is detected, or in the course of upstream wavelength channel locking (see clause 17.4).	The ONU adjusts transmitter wavelength. No Acknowledgement.
0x15	Tuning_Control	In TWDM mode of operation, to initiate (Operation code: Request) or to confirm completion (Operation code: Complete_d) of ONU wavelength channel (or wavelength channel pair) handover operation. No function in TDM mode of operation.	The decision by the source OLT CT to initiate ONU wavelength channel handover operation (Operation code: Request); or a successful receipt by the target OLT CT of an upstream transmission from the ONU being handed over (Operation code: Complete_d).	Operation code: Request. The ONU sends a Tuning_Response PLOAM message with an appropriate operation code (ACK, if the ONU intends to execute the command; NACK, if the ONU is unable to execute the command). Operation code: Complete_d. The ONU recognizes successful completion of the wavelength channel handover, sends an Acknowledgement PLOAM message.
0x17	System_Profile	Broadcast message containing a copy of the system descriptor (see clause 17.1.1). Partially retains functionality in TDM mode of operation.	Periodically with programmable periodicity.	The ONU stores the profile information or updates the profile information previously stored for use in subsequent channel management and operation tasks. No Acknowledgement.
0x18	Channel_Profile	Broadcast message containing a copy of one downstream wavelength channel descriptor and one upstream wavelength channel descriptor (see clause 17.1.1).	Periodically with programmable periodicity.	The ONU stores the profile information or updates the profile information previously stored for use in subsequent channel management and operation tasks. No Acknowledgement.

Table 11-3 – Downstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x19	Protection_ Control	In TWDM mode of operation, unicast or broadcast message that specifies the pre-configured protection TWDM channel. No functionality in TDM mode of operation.	At the implementor's discretion.	The ONU stores the pre-configured protection TWDM channel information, sends an Acknowledgement PLOAM message. An ONU in TDM mode sends an acknowledgement with Unsupported operation mode code.
0x1A	Change_Power _Level	To instruct an ONU to change and/or to report its launch optical power level.	At the implementor's discretion.	The ONU adjusts its launch optical power level as instructed and, if responding to a directed Change_Power_Level message, sends an Acknowledgement PLOAM message.
0x1B	Power _Consumption _Inquire	In TWDM to inquire the power consumption information.	At the OLT's discretion.	Send one Power_Consumption_ Report message for power consumption information.
0x1D	Reboot_ONU	Broadcast or unicast message to cause one or more ONUs to reboot	At the implementer's discretion	This is downstream only message and OLT does not expect ACK for this message. All addressed ONUs are expected to reboot.
0x1E	Bonded_Channel _Status	Broadcast or unicast message to control ONU upstream channel bonding	At the OLT's discretion.	The ONU bonds/suspends/resumes its upstream channel(s) as instructed and sends a Bonded_Channel_Response message.
0x1F	Get_Set_Capabilities	Unicast message to query an ONU on its feature support, or set an ONU's feature setting.	At the OLT's discretion.	The ONU sends an ONU_Capabilities message as acknowledgement and to indicate its feature support capabilities

11.3.2 Upstream PLOAM message summary

Table 11-4 summarizes the upstream messages.

Table 11-4 – Upstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x01	Serial_Number_ ONU	To report the serial number of an activating ONU; in a TWDM system, also to report the calibration accuracy and the tuning characteristics.	An ONU in the Serial Number state (O2-3) sends a Serial_Number_ONU message in response to an SN grant.	The OLT CT detects an activation attempt, discerns the activating ONU's serial number, calibration accuracy and tuning characteristics and provides feedback to the activating ONU, which can be in the form of Assign_ONU-ID or Adjust_Tx_ Wavelength PLOAM messages.
0x02	Registration	To report the Registration_ID of an ONU.	When the ONU is in the Ranging state (O4) or is responding to a ranging grant, or when the ONU is in the Operation state (O5) and is responding to the Request_ Registration message.	The OLT CT may use the ONU's Registration_ID as described further in clause 15.2.1.
0x05	Key_Report	To send a fragment of a new data encryption key or a hash of an existing data encryption key.	When the ONU receives the Key_Control message and has generated new keying material.	See clause 15.5.1 for the details of the protocol.
0x09	Acknowledgement	To indicate reception of specified downstream messages, to report PLOAM processing error, or to provide busy or no-message indication.	Upon receipt of a downstream message that requires acknowledgement, or when an upstream PLOAM allocation is granted, but no other message is available for transmission.	The OLT CT uses a received Acknowledgement PLOAM message to verify integrity of the PLOAM channel with the given ONU.

Table 11-4 – Upstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x10	Sleep_Request	To signal the ONU's intention to start or terminate power saving	When the ONU power management state machine (see clause 16.3.1) triggers a change between active behaviour and power saving behaviour.	The OLT either grants the ONU request or instructs it to remain at full power, according to the OLT power management state machine of clause 16.3.2.
0x1A	Tuning_Response	(1) To respond to the Tuning_Control PLOAM message with Request operation code, indicating either the intent or the inability to execute the tuning request, along with the applicable response code (2) To provide an indication of the success or failure of a wavelength tuning operation along with the applicable response code.	When an ONU in the Operation state (O5) receives a Tuning_Control PLOAM message with the Request opcode; or when an ONU in the Upstream Tuning state (O9) receives an upstream in-band PLOAM grant upon completion of an upstream wavelength tuning operation, depending on whether or not the ONU meets the specified calibration accuracy constraints.	The OLT CT executes appropriate ICTP transaction commit operation, and generates downstream PLOAM messages, according to the protocol specification of clause 17.
0x1B	Power _Consumption _Report	To provide power consumption information.	Upon receipt of a Power_Consumption _Inquire message.	The OLT CT tunes the ONU to the optimized TWDM channel for operation in terms of power consumption information.
0x1D	Bonded_Channel_ Response	To respond to the Bonded_Channel_Status message, indicating the upstream channel bonding status.	Upon receipt of a Bonded_Channel_Sta tus message.	The OLT CT executes appropriate operation.

Table 11-4 – Upstream PLOAM messages

Message type ID	Message name (applicability)	Function	Trigger	Effect of receipt
0x1E	ONU_Capabilities	To indicate ONU support for capabilities and acknowledgement.	Upon receipt of a Get_Set_Capabilties unicast message.	The OLT records the capabilities of the ONU and may use this information to invoke specific capabilities. The OLT gets confirmation if the requested Get_Set_Capabilities command has been accepted.

11.3.3 Downstream PLOAM message formats

11.3.3.1 Burst_Profile message

Burst profile information is transmitted periodically, at intervals of hundreds of milliseconds or longer. The version of a specific burst profile definition may change over time, so an ONU is expected to update itself with the latest version each time the message appears. To ensure that all ONUs are up to date, the OLT CT is expected not to make use of the changed information until each ONU has had a chance to receive the updated burst profile at least twice while it is in either ActiveFree or ActiveHeld power management state. (See clause 16.3.1 for ONU power management state machine description.)

The burst profile information accumulated by the ONU does not persist across ONU activations. A newly activated ONU may respond to a serial number grant only after it has acquired the burst profile information associated with the grant. More generally, an ONU in any state can respond to an allocation structure only if it has previously acquired the corresponding burst profile information.

The OLT CT is responsible to understand the consequences of sending both broadcast and unicast Burst_Profile messages. Specifically, a subsequent broadcast Burst_Profile message overwrites all unicast profiles with the same burst profile index.

Information on Burst_Profile message is provided in Table 11-5.

Table 11-5 – Burst_Profile message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all ONUs. As a broadcast to all ONUs, ONU-ID = 0x03FF.
3	Message type ID	0x01, "Burst_Profile".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.

Table 11-5 – Burst_Profile message

Octet	Content	Description
5	Burst profile control 1	An octet of the form VVVB BBPP, where: VVV – Three-bit burst profile version. If the content of the burst profile changes, the OLT CT should ensure that the version also changes, so that the ONU can detect updates solely on the basis of the version field. BBB – Codepoint indicating the applicability of the message to specific upstream line rates. The codepoints are specified in the applicable PMD Recommendations. PP – Two-bit burst profile index.
6	Burst profile control 2	NNMM RRCF, where: NN – Total number of PSBu segments minus 1, range 0..3. MM – zero-based contiguous PSBu segment sequence number, range 0..NN. PSBu segments transmitted on the optical channel will be concatenated in the order provided by this field, where zero corresponds to the PSBu segment transmitted first. If MM>NN, then discard the message.C – Cross-channel burst profile indicator (TWDM only) C = 0: The burst profile is applicable to this channel C = 1: The burst profile is applicable as if it was transmitted in the downstream wavelength channel identified by Downstream PON ID provided by octets 35-38 of this message. F – Upstream FEC indication: F = 1: FEC on; F = 0: FEC off. R – reserved, set to 0 by the transmitter. The content of NN, C and F are set and are valid only in the first message corresponding to a particular burst profile (i.e., when MM=0).
7	Delimiter control	RRRR RRDD, where: DD – Delimiter length in 32-bit words; two-bit integer, range 0..2. R – Reserved, set to 0 by the transmitter.
8-15	Delimiter pattern	Aligned with the most significant end of the field; padded with 0x00; padding treated as "don't care" by the receiver.
16	Preamble descriptor	TRRL LLLL, where: T – Preamble pattern type T = 0: predefined preamble pattern T = 1: custom preamble pattern;RR – Reserved, set to 0 by the transmitter. -LLLLL – if T = 0: set to 00000; treated as "don't care" by the receiver. T = 1: preamble pattern length in multiples of 4 bits, range 1..16; LLLLL = 2 for example, specifies a preamble pattern length of 8 bits.

Table 11-5 – Burst_Profile message

Octet	Content	Description
17-18	Preamble word count	Preamble word count, in 64 bit words, range 0..w_{max}, where w_{max} denotes the maximum word count, and should depend on the upstream line rate. The value 0 specifies that no preamble is transmitted. It is moreover required that the sum of the values of this field across all PSBu segments does not exceed w_{max}. The value of w_{max} is equal to the number of 64-bit words sent during 1,000 time quanta at the applicable line rate.
19-26	Preamble pattern	Specification of the preamble pattern. If: T = 0: Custom pattern in big-endian bit format (most significant bit is transmitted on the optical channel first), aligned with the most significant end of the field; padded with 0; padding treated as "don't care" by the receiver. T = 1: The three initial octets of this field assume the following structure: RRRR PPPP SSSS SSSS SSSS SSSS, where: R – Reserved, set to 0 by the transmitter; PPPP – Predefined pattern codepoint: PPPP = 0111: pseudorandom binary sequence of order 7 (PRBS7) padded with zero; PPPP = 1000: PRBS8 padded with zero; PPPP = 1001: PRBS9 padded with zero; PPPP = 1010: PRBS10 padded with zero; PPPP = 1011: PRBS11 padded with zero; PPPP = 1100: PRBS12 padded with zero; PPPP = 1101: PRBS13 padded with zero; PPPP = 1110: PRBS14 padded with zero; PPPP = 1111: PRBS15 padded with zero; Detailed specification of predefined preamble patterns can be found in Annex I. SSSS SSSS SSSS SSSS – seed (n initial bits) used for generation of PRBS order n, encoded in n least significant bits. The most significant non-zero bit corresponds to the highest order tap x^n. The value zero shall not be used. Discussion on recommended seeds can be found in Appendix III.1. The remaining octets of this field are set to 0x00 by the transmitter; treated as "don't care" by the receiver.
27-34	PON-TAG	An 8-byte static attribute of the OLT CT that is chosen by the operator and is used to bind the master session key (MSK) to the context of the security association (see clause 15.3.3). Unless the profile version is incremented, PON-TAG is the same for Burst_Profile messages with all profile indices transmitted by the OLT CT. It is good practice to ensure that PON-TAG is unique within at least the operator's domain and fixed for the lifetime of the system. The content of this field are set and are valid only in the first message corresponding to a particular burst profile (i.e., when MM=0).

Table 11-5 – Burst_Profile message

Octet	Content	Description
35-38	Downstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the downstream wavelength channel to which the burst profile of the present PLOAM message is applicable. For C=0, set to PON-ID of the OC structure. The content of this field are set and are valid only in the first message corresponding to a particular burst profile (i.e., when MM=0).
39	ONURssiMin	This is an 8-bit unsigned integer field, representing the downlink minimum received signal strength indicator (RSSI) threshold for activation. Only the ONUs with measured downlink RSSI greater or equal to ONURssiMin shall respond to a SN grant. The unit of ONURssiMin value is 0.1 dBm, its value is an integer representing a logarithmic power measure having 0.1 dB granularity with respect to −28.0 dBm (e.g., the value 0x40 represents −28.0+100*0.1= −18.0 dBm, 0x01 represents −27.9 dBm, and 0xFF represents −2.5 dBm). The 0x00 default value indicates that ONURssiMin is −infinite dBm, all ONUs can satisfy this field. The content of this field are set and are valid only in the first message corresponding to a particular burst profile (i.e., when MM=0).
40	ONURssiMax	This is an 8-bit unsigned integer field, representing the downlink maximum received signal strength indicator (RSSI) threshold for activation. Only the ONUs with measured downlink RSSI lower or equal to ONURssiMax shall respond to a SN grant. The unit of ONURssiMax value is dBm, its value is an integer representing a logarithmic power measure having 0.1 dB granularity with respect to −28.0 dBm (e.g., the value 0x00 represents −28.0dBm, 0x40 represents −28.0+100*0.1= −18.0 dBm, and 0xFE represents −2.6 dBm). The 0xFF default value indicates that ONURssiMax is +infinite dBm, all ONUs can satisfy this field. The content of this field are set and are valid only in the first message corresponding to a particular burst profile (i.e., when MM=0).
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.3.2 Assign_ONU-ID message

Information regarding Assign_ONU-ID message is provided in Table 11-6.

Table 11-6 – Assign_ONU-ID/Collision_Feedback message

Octet	Content	Description
1-2	ONU-ID	0x03FF, Broadcast ONU-ID.
3	Message type ID	0x03, "Assign_ONU-ID/Collision_Feedback".
4	SeqNo	Eight-bit broadcast PLOAM sequence number.

Table 11-6 – Assign_ONU-ID/Collision_Feedback message

Octet	Content	Description
5-6	ONU-ID	ONU-ID being assigned, or ONU-ID of the successful ONU LSB-justified 10-bit assigned ONU-ID value padded with six MSB zeros; range 0..1019 (0x0000..0x03FB). If the transmission has not been successful (no ONU-ID assigned and no ONU has communicated its PLOAM message) the field is set to 0xFFFF and ignored by the receiving ONUs.
7-10	Vendor_ID	See clause 11.2.6.1. 0x00 if not used (ONU-ID set to 0xFFFF)
11-14	VSSN	See clause 11.2.6.2. 0x00 if not used (ONU-ID set to 0xFFFF)
15	Upstream nominal line rate indicator	0000 00UU, where: U – upstream nominal line rate, UU = 00, Upstream nominal line rate $\rho_0\phi_0$; UU = 01, Upstream nominal line rate $\rho_0\phi_1$ UU = 10, Upstream nominal line rate $\rho_0\phi_2$ This indicator is only applicable for an ONU supporting multiple upstream line rates to select the instructed upstream nominal line rate to operate.
16–17	Alloc-ID	The Alloc-ID value that has been a recipient of the contention-based allocation to which the feedback is being provided. 14 bits, aligned to the least significant end. The most significant bits are set to 0 by the transmitter and treated as "don't care" by the receiver.
18	Allocation feedback	C000FFDD, C – continuation flag 0 – the last message of the allocation feedback 1 – another message to follow FF – major level feedback 00 – not evaluated 01 – idle allocation 10 – successful ONU-ID assignment 11 – collision DD – detailed feedback on the other events of the allocation interval 00 – not evaluated 01 – idle 10 – well-formed burst 11 – collision
19-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.3 Ranging_Time message

In its typical application, the Ranging_Time message is used to establish the equalization delay for a given ONU (directed message), as described in clause 12. As a broadcast message, the Ranging_Time message may be used to specify a delay offset adjustment, either positive or negative, to all ONUs, after a protection switching event. The OLT CT is responsible to consider the interaction between broadcast Ranging_Time and possible power management states of its ONUs. Information regarding Ranging_Time message is provided in Table 11-7.

Table 11-7 – Ranging_Time message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all ONUs. As a broadcast to all ONUs, ONU-ID = 0x03FF.
3	Message type ID	0x04, "Ranging_Time".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number.
5	Control octet	An octet of the form 0000 0XSP that indicates how the EqualizationDelay field is to be interpreted. P = 1: The delay in bytes 6..9 is absolute; ignore S. P = 0: The delay in bytes 6..9 is relative; S determines sign. S = 0: Positive: increase the current EqD by the specified value. S = 1: Negative: decrease the current EqD by the specified value. X = 0: The delay in bytes 6..9 is for current downstream/upstream wavelength pair, ignore bytes 10 to 13 and 14 to 17. X = 1: The delay in bytes 6..9 is for the downstream/upstream wavelength pair specified in bytes 10 to 13 and 14 to 17.
6-9	Equalization-Delay	Equalization delay value, expressed in $Q_0/32$.
10-13	Downstream PON-ID	The 32-bit PON-ID of the channel profile that contains the downstream descriptor of the channel pair for which the equalization delay is established. The default is the PON-ID of the OC structure.
14-17	Upstream PON-ID	The 32-bit PON-ID of the channel profile that contains the upstream descriptor of the channel pair for which the equalization delay is established. The default is the PON-ID of the OC structure.
18-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.3.4 Deactivate_ONU-ID message

Information regarding Deactivate_ONU-ID message is provided in Table 11-8.

Table 11-8 – Deactivate_ONU-ID message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all ONUs. As a broadcast to all ONUs, ONU-ID = 0x03FF.
3	Message type ID	0x05, "Deactivate_ONU-ID".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.

Table 11-8 – Deactivate_ONU-ID message

Octet	Content	Description
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.5 Disable_Serial_Number message

Information regarding Disable_Serial_Number message is provided in Table 11-9.

Table 11-9 – Disable_Serial_Number message

Octet	Content	Description
1-2	ONU-ID,	0x03FF, Broadcast ONU-ID.
3	Message type ID	0x06, "Disable_Serial_Number".
4	SeqNo	Eight-bit broadcast PLOAM sequence number.
5	Disable/enable	0xFF: The ONU with this serial number is denied upstream access. 0x00: The ONU with this serial number is allowed upstream access. 0x0F: All tuned-in ONUs are denied upstream access. The content of bytes 6..13 is ignored. 0x3F: Disable_Discovery: the tuned-in ONUs in O2-3 state are denied upstream access. The content of bytes 6..13 is ignored. 0xF0: All tuned-in ONUs are allowed upstream access.
6-9	Vendor_ID	See clause 11.2.6.1.
10-13	VSSN	See clause 11.2.6.2.
14-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.6 Request_Registration message

Information regarding Request_Registration message is provided in Table 11-10.

Table 11-10 – Request_Registration message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU.
3	Message type ID	0x09, "Request_Registration".
4	SeqNo	Eight-bit unicast PLOAM sequence number.
5-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.

11.3.3.7 Assign_Alloc-ID message

Information regarding Assign_Alloc-ID message is provided in Table 11-11.

Table 11-11 – Assign_Alloc-ID message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message for the contention-based Alloc-ID assignment. As a broadcast message, ONU-ID = 0x03FF.
3	Message type ID	0x0A,"Assign_Alloc-ID".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5-6	Alloc-ID-value	14 bits, aligned to the least significant end. The most significant bits are set to 0 by the transmitter and treated as "don't care" by the receiver.
7	Alloc-ID-type	0x01: XGEM-encapsulated payload. 0xFF: Deallocate this Alloc-ID. Other values reserved.
8-9	Alloc-ID scope	A bitmap indexed by UWLCH ID; the MSB of octet eight correspond to UWLCH ID = 1111; the LSB of octet nine corresponds to UWLCH ID = 0000. The bit value of 1 indicates that the specified Alloc-ID is invalid in the corresponding upstream wavelength channel. Normally, the OLT CT assigns Alloc-ID scope that includes all upstream wavelength channels in the TWDM system. Assignment of narrow scopes is for future study. The ONU does not respond to an allocation to a directed Alloc-ID if it is invalid in the given upstream wavelength channel. The OLT CTs should coordinate Alloc-ID assignment to ensure that each unique Alloc-ID is assigned to at most one contention-based function, or to at most one ONU in a TWDM PON system. In a fixed-wavelength TDM system using the default UWLCH ID of 1111, this field is set to 0x7F.
10	Contention-based function ID	In broadcast messages for contention-based Alloc-ID assignment, See Table 7-1. In directed messages, set to 0x00 by the transmitter and ignored by the receiver.
11-18	Contention-based function parameters	In broadcast messages for contention-based Alloc-ID assignment, See Table 7-1. In directed messages, set to 0x00 by the transmitter and ignored by the receiver.
19-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using either the ONU-specific derived shared PLOAM integrity key (directed message), or a default PLOAM integrity key (broadcast message).

11.3.3.8 Key_Control message

Information regarding Key_Control message is provided in Table 11-12.

Table 11-12 – Key_Control message

Octet	Content	Description
1-2	ONU-ID	Directed or broadcast message to instruct one or all tuned-in ONUs to generate new keying material or confirm their existing keys. As a broadcast message, ONU-ID = 0x03FF.
3	Message type ID	0x0D, "Key_Control".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5	Reserved	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
6	Control flag	0000 000C, where C = 0: Generate and send a new key. C = 1: Confirm the existing key.
7	Key index	0000 00BB, where BB – Key index 01: First key of a key pair. 10: Second key of a key pair.
8	Key_Length	Required key length, bytes. The value zero specifies a key of 256 bytes (Note).
9-24	Random number X	OLT generated random 128-bit number intended to be used as KeyControl_RandomX variable in 128-bit EK calculation (see clause 15.5.2).
25-40	Random number Y	OLT generated random 128-bit number, where X ≠ Y, intended to be used as KeyControl_RandomY variable in 256-bit EK calculation (see clause 15.5.2).
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.
NOTE – This parameter supports the long-term extensibility of the data encryption key exchange protocol. The default cryptographic method for the data encryption, the AES-128 cipher (see clause 15.4) uses the fixed size key of 16 bytes.		

11.3.3.9 Sleep_Allow message

Information regarding Sleep_Allow message is provided in Table 11-13.

Table 11-13 – Sleep_Allow message

Octet	Content	Description
1-2	ONU-ID	Directed or broadcast ONU-ID. As a broadcast message, ONU-ID = 0x03FF.
3	Message type ID	0x12, "Sleep_Allow".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5	Control flag	0000 000A, where: A = 0: Sleep allowed OFF. A = 1: Sleep allowed ON. Other values reserved.

Table 11-13 – Sleep_Allow message

Octet	Content	Description
6-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.3.10 Calibration_Request message

Information regarding Calibration_Request message is provided in Table 11-14.

Table 11-14 – Calibration_Request message

Octet	Content	Description
1-2	ONU-ID	Unassigned ONU-ID
3	Message type ID	0x13, "Calibration_Request"
4	SeqNo	0x00
5-8	Vendor_ID	See clause 11.2.6.1.
9-12	VSSN	See clause 11.2.6.2.
13-16	Current PON-ID	Identity of the CT that terminates the upstream wavelength channel where the transmission has been successfully received.
17-18	Correlation tag	See clause 11.2.6.3.
19-22	Target downstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the target downstream wavelength channel.
23-26	Target upstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the target upstream wavelength channel.
27-40	Padding	Set to 0x00 by transmitter, treated as "don't care" by receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.11 Adjust_Tx_Wavelength message

Information regarding Adjust_Tx_Wavelength message is provided in Table 11-15.

Table 11-15 – Adjust_Tx_Wavelength message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or unassigned ONU-ID. When directed message to one ONU, Vendor_ID and VSSN are both filled with 0. When directed message to unassigned ONU-ID (0x03FF), Vendor_ID and VSSN are both filled with valid value.
3	Message type ID	0x14, "Adjust_Tx_Wavelength".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5-8	Vendor_ID	See clause 11.2.6.1.

Table 11-15 – Adjust_Tx_Wavelength message

Octet	Content	Description
9-12	VSSN	See clause 11.2.6.2.
13-16	Current PON-ID	An identity of the CT that terminates the upstream wavelength channel where the transmission has been successfully received.
17-18	Correlation tag	See clause 11.2.6.3.
19	Frequency adjustment direction	0000 000D, where: D – Transmitter frequency adjustment direction D = 0: adjust ONU transmitter to lower frequency D = 1: adjust ONU transmitter to higher frequency
20-21	Frequency adjustment size	An unsigned integer indicating the size of the frequency adjustment in units of 0.1 GHz.
22-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.12 Tuning_Control message

The Tuning_Control PLOAM message is used in the process of ONU wavelength channel handover (see clause 17.3). Information regarding Tuning_Control message is provided in Table 11-16.

Table 11-16 – Tuning_Control message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU.
3	Message type ID	0x15, "Tuning_Control".
4	SeqNo	Eight-bit unicast PLOAM sequence number.
5	Operation Code	0x00: Request; All parameters are applicable. 0x01: Complete_d Target downstream and upstream PON-ID parameters are applicable. Octets 6..8 and 17 are set to 0x00 by the OLT CT and ignored by the ONU.
6-7	Scheduled SFC	The 16 least significant bits of the superframe counter value of the PHY frame in the future when the ONU has to commence the transceiver tuning operation. The specified value pertains to both downstream and upstream tuning. Whenever separate tuning is deemed beneficial, two unidirectional tuning actions executed serially can be considered.
8	Rollback flag	A bitmap of the form 0000 000R, where: R – Rollback flag R=1: rollback available when tuning fails; R=0: no rollback available when tuning fails.
9-12	Target downstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the target downstream wavelength channel.

Table 11-16 – Tuning_Control message

Octet	Content	Description
13-16	Target upstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the target upstream wavelength channel.
17	Calibration flag	A bitmap of the form 0000 000R, where: R – Calibration flag R = 0: if ONU has no calibration information for target wavelength channel, the ONU responds with NACK by lack of calibration and ignores tuning request; R = 1: if ONU has no calibration information for target wavelength channel, the ONU should execute tuning request with necessary calibration.
18-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check. computed using the default PLOAM integrity key.

11.3.3.13 System_Profile message

Table 11-17 focuses on the encoding of the PLOAM message octets. For the detailed explanation of the profile parameters, see clause 17.1.1.

Table 11-17 – System_Profile message

Octet	Content	Description
1-2	ONU-ID	0x03FF, Broadcast ONU-ID.
3	Message type ID	0x17, "System_Profile".
4	SeqNo	Eight-bit broadcast PLOAM sequence number.
5-7	SYS ID	The 20-bit identity of the TWDM system within a certain domain. This is a reference value set by the OSS. The eight LSBs of SYS ID are in Octet 7; the four MSBs of SYS ID are in the LSB nibble of Octet 5. The four MSBs of Octet 5 are zeros.
8	System profile version	VVVV 0000, where: VVVV – Four-bit system profile version. If the content of the system profile changes, the OLT CT should ensure that the version also changes, so that the ONU can detect updates solely on the basis of the version field.
9	Upstream operating wavelength bands	000P 00TT, where: P is reserved and set to 0 by transmitter: TT is encoded TWDM upstream operating wavelength band: 00: Wide band option; 01: Reduced band option; 10: Narrow band option. See the applicable PMD Recommendations for the details of band options.

Table 11-17 – System_Profile message

Octet	Content	Description
10	TWDM channel count	0000 CCCC, where: CCCC – an unsigned integer indicating the number of TWDM channels that exist in the system, each described with a Channel_Profile PLOAM message with a distinct Channel profile identifier.
11	Channel spacing	An unsigned integer indicating the value in units of 1 GHz. Note – Channel spacing is a system parameter characterizing the grid to which the system is designed, rather than how the wavelength channels are deployed.
12	Upstream MSE	Maximum spectral excursion (MSE) represented as an unsigned integer indicating the value in units of 1 GHz.
13-14	FSR	If a cyclic wavelength multiplexer (WM) is used in the upstream, free spectral range (FSR) is represented as an unsigned integer indicating the value in units of 0.1 GHz. If a cyclic WM is not used, this field contains 0x0000.
15	TWDM control	An octet of the form 0A00 00BB, where: A – reserved and set as 0 by transmitter: BB – minimum calibration accuracy required for in-band activation 00: reserved, protected 01: uncalibrated 10: loose 11: sufficient
16	Loose calibration bound for TWDM channels	Spectral excursion bound below which a TWDM ONU can be considered as loosely calibrated. Represented as an unsigned integer indicating the value in units of 1 GHz. 0x00: use upstream TWDM MSE value.
17-24	PtP Reserved	Reserved and set as 0 by transmitter.
25-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.14 Channel_Profile message

Table 11-18 focuses on the encoding of the PLOAM message octets. For the detailed explanation of the profile parameters, see clause 17.1.1.

Table 11-18 – Channel_Profile message

Octet	Content	Description
1-2	ONU-ID	0x03FF, Broadcast ONU-ID.
3	Message type ID	0x18, "Channel_Profile".
4	SeqNo	Eight-bit broadcast PLOAM sequence number.

Table 11-18 – Channel_Profile message

Octet	Content	Description
5	Control octet	An octet of the form CCCC 0TDU, where: CCCC – Channel profile identifier which is unique for each TWDM channel that exists in the system. The allocated channel profile identifiers are only required to be distinct, and do not have to be consecutive or ordered in any particular way. T – *This* channel indicator: T = 0: The channel profile pertains to another TWDM channel T = 1: The channel profile pertains to the TWDM channel in which it is transmitted (necessarily, D = 0) D – Downstream void indicator: D = 0: Downstream descriptor valid D = 1: Downstream descriptor to be ignored U – Upstream void indicator: U = 0: Upstream descriptor valid U = 1: Upstream descriptor to be ignored Flags T, D, and U enable a downstream transmission to supply a descriptor for an upstream channel.
6	Channel profile version	VVVV 0000, where: VVVV – Four-bit channel profile version If the content of the channel profile changes, the OLT CT should ensure that the version also changes, so that the ONU can detect updates solely on the basis of the version field.
7-10	PON-ID	A 32-bit static value which is carried in the operation control (OC) structure of each downstream PHY frame in the specified TWDM channel (see clause 10.1.1.3); consists of 28-bit administrative label (octets 7 through 9 and 4 MSBs of octet 10) and DWLCH ID (4 LSBs of octet 10).
11	Downstream frequency offset	The difference (if known) between the actual OLT CT Tx frequency and the nominal central frequency for the given DWLCH ID (see Table 6-4), represented as a signed integer in complementary code, and expressed in units of 0.1 GHz. 0000 0000: zero offset 1000 0000: offset not known
12	Downstream rate	Octet of the form 0SSE LLLL with the following encoding: SS – downstream ComTC layer line rate, the codepoints are specified in the applicable PMD Recommendations. E – Downstream FEC: E = 0: FEC OFF E = 1: FEC ON LLLL – downstream line code (see the applicable PMD Recommendations) 0000: NRZ Other codepoints are for future study.
13	Channel partition	Octet of the form 0000 PPPP, where PPPP – Channel partition index.

Table 11-18 – Channel_Profile message

Octet	Content	Description
14-17	Default response channel	32-bit PON-ID of the Channel_Profile message containing the descriptor of the upstream wavelength channel to use (see Table 17-2).
18	Serial number grant type indication	Reserved, set as 0 by transmitter.
19-22	AMCC window specification	Reserved, set as 0 by transmitter.
23	UWLCH ID	An octet of the form 0000 UUUU, where UUUU is the assigned upstream wavelength channel ID.
24-27	Upstream frequency	The nominal central frequency of the upstream wavelength channel or a root frequency of the cyclic set of central frequencies forming an upstream wavelength channel, expressed as an unsigned integer indicating the value in units of 0.1 GHz.
28	Optical link type	0000 00AB A bitmap representation of the upstream optical link type. A – Type A support: A = 0:Type A not supported; A = 1:Type A supported. B – Type B support: B = 0:Type B not supported; B = 1:Type B supported.
29	Upstream rate	Bitmap of the form 0000 ABCL with the following encoding: A – Upstream nominal line rate $\rho_0 \phi_0$ A = 0: not supported; A = 1: supported. B – Upstream nominal line rate $\rho_0 \phi_1$ B = 0: not supported; B = 1: supported. C – Upstream nominal line rate $\rho_0 \phi_2$ C = 0: not supported; C = 1: supported. L – reserved, set as 0 by transmitter.
30	Default ONU attenuation	An octet of the form 0000 MMMM, where: MMMM – the default ONU attenuation level 0000: No attenuation requested; 0001..0111: the default attenuation level in steps of 3 dB. See clause 12.6.1.
31	Response threshold	An unsigned integer representing the maximum number of PLOAM messages the ONU can transmit at non-zero attenuation level while attempting to establish communication with OLT CT. Zero, if the OLT CT does not encourage ONU-activated power levelling. See clause 12.6.

Table 11-18 – Channel_Profile message

Octet	Content	Description
32	Cloned configuration	An octet of the form 0xAB where: A = 0000 – this is a regular system; A = 0001 – this is a cloned system. B is applicable to *This* channel only as indicated in Octet 5 (and should be set to 0x00, otherwise) B = 0000 – this is a common channel termination; otherwise, a non-zero value of B is the operator-assigned instance identifier of the cloned subtree the channel termination belongs to, as specified by the OLT side.
33-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.15 Protection_Control message

Information regarding Protection_Control message is provided in Table 11-19.

Table 11-19 – Protection_Control message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all ONUs of one downstream wavelength.
3	Message type ID	0x19, "Protection_Control".
4	SeqNo	Eight-bit broadcast or unicast PLOAM sequence number, as appropriate.
5-8	Protection downstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the protection downstream wavelength channel.
9-12	Protection upstream PON-ID	The 32-bit PON-ID of the channel profile that contains the descriptor for the protection upstream wavelength channel.
13	Enable/disable flag	If set to 0x00, enables wavelength channel protection for the given ONU using specified downstream and upstream protection PON-IDs (the WLCP indication returns Boolean TRUE or ON); otherwise, disables wavelength channel protection for the given ONU (the WLCP indication returns Boolean FALSE or OFF). In the latter case, the PON-IDs in octets 5..12 are ignored.
14-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.3.16 Change_Power_Level message

Information regarding Change_Power_Level message is provided in Table 11-20.

Table 11-20 – Change_Power_Level message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all tuned-in ONUs.
3	Message type ID	0x1A, "Change_Power_Level".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5	Operation type	0000 00TT TT – Operation type: 00: direct attenuation level control; 01: decrease launch optical power by applying next supported attenuation level; 10: increase launch optical power by applying next supported attenuation level; 11: request current attenuation level. If the ONU is unable to change its launch optical power because it is already at its maximum (or minimum) setting, or if the specified attenuation level is not supported, then the ONU should not execute this request, responding with an Acknowledgement message containing the completion code that indicates a Parameter Error.
6	Attenuation	See clause 11.2.6.7.
7-40	Padding	Set to 0x00 by the transmitter and treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.3.17 Power_Consumption_Inquire message

Information regarding Power_Consumption_Inquire message is provided in Table 11-21.

Table 11-21 – Power_Consumption_Inquire message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all tuned-in ONUs.
3	Message type ID	0x1B, "Power_Consumption_Inquire".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM_IK in case of broadcast message, and using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.3.18 Reboot_ONU message

Table 11-22 describes the Reboot ONU message.

Table 11-22 – Reboot_ONU message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all ONUs. A single ONU is addressed in this message either through an assigned ONU-ID or through Vendor_ID and VSSN with ONU-ID set to 0x3FF (broadcast ID). All ONUs are addressed on the PON when ONU-ID is set to 0x3FF (broadcast ID) and Vendor-ID and VSSN fields are set to 0x00.
3	Message type ID	0x1D, "Reboot_ONU".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number, as appropriate.
5-8	Vendor_ID	See clause 11.2.6.1. This field is inspected only when ONU-ID is set to 0x03FF (broadcast ID).
9-12	VSSN	See clause 11.2.6.2. This field is inspected only when ONU-ID is set to 0x03FF (broadcast ID).
13	Reboot depth	This field defines the enumerated values: 0x0 MIB reset (MIB reset is defined in clause 9.1.3 of ITU-T G.988) 0x1 Perform equivalent of OMCI reboot (clause A.2.35 of ITU-T G.988) 0x2 Perform equivalent of power cycle reboot 0x3 Configuration reset, then perform MIB reset and reboot* 0x4..0xFF Reserved *Sometimes ONU may not come up even after OMCI reboot or power-cycle reboot due to saved configuration in the non-volatile memory of the ONUs. When action is set to 0x3, ONU will reset, clear its previously saved configuration (e.g., VoIP configuration and dual managed ONU configuration), perform a MIB reset and then reboot. Factory configuration (serial number and MAC) and registration ID, software images and indication of which image is committed should not be affected by this action. These mechanisms are intended to be used as a last resort to revive the ONU. Note – Applicable ONU states of the Reboot_ONU PLOAM is up to the implementation.
14	Reboot Image	This field defines which image will be loaded and executed (i.e., which image will be active) upon reboot using the enumerated values: 0x0 Load and execute the image that is currently committed 0x1 Load and execute the image that is not currently committed This field is ignored when Reboot depth = 0x0
15	ONU State	This field defines the enumerated values: 0x0 Reboot if ONU is in any state 0x1 Reboot only if ONU is in states O1, O2-3

Table 11-22 – Reboot_ONU message

Octet	Content	Description
16	Flags	Bits 2-1: 00 Reboot regardless of POTS/VoIP call state 01 Reboot only if no POTS/VoIP calls are in progress 10 Reboot only if no emergency call is in progress 11 Reserved Bits 8-3: Reserved
17-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the default PLOAM integrity key.

11.3.3.19 Bonded_Channel_Status message

Information regarding Bonded_Channel_Status message is provided in Table 11-23.

Table 11-23 – Bonded_Channel_Status message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU or broadcast message to all ONUs. As a broadcast to all ONUs, ONU-ID = 0x03FF. Only bonded ONUs can understand and respond to this message
3	Message type ID	0x1E, "Bonded_Channel_Status".
4	SeqNo	Eight-bit unicast or broadcast PLOAM sequence number.
5	Opcode/Correlation ID	0x00: Status request, the remainder of the message shall be ignored. Non zero code: Instruction Correlation ID
6-13	Wavelength channel 1..8 status	Wavelength channel status: 0x00 – Bond (if present) 0x01 – Suspend (if present) 0xFF – Known to be absent Other code points reserved
14-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.

11.3.3.20 Get_Set_Capabilities message

Table 11-24 describes the Get_Set_Capabilities message.

Table 11-24 – Get_Set_Capabilities message

Octet	Content	Description
1-2	ONU-ID	Directed message to one ONU.
3	Message type ID	0x1F, " Get_Set_Capabilities ".
4	SeqNo	Eight-bit unicast sequence number.

Table 11-24 – Get_Set_Capabilities message

Octet	Content	Description
5	ONU Capability Query/Set	An octet of the form RRRR RRRS, where: S = 0: Query of the ONU capability. S = 1: Setting of the ONU capability. R – reserved, set to 0 by the transmitter; treated as "don't care" by the receiver.
6-40	Reserved	Reserved and set as 0 by transmitter
41-48	MIC	Message integrity check, computed using the ONU-specific derived shared PLOAM_IK in case of directed message.

11.3.4 Upstream PLOAM message formats

11.3.4.1 Serial_Number_ONU message

Information regarding Serial_Number_ONU message is provided in Table 11-25.

Table 11-25 – Serial_Number_ONU message

Octet	Content	Description
1-2	ONU-ID	0x03FF, Unassigned ONU-ID; or in case of an ONU with multiple PON interfaces undergoing activation on the second and subsequent PON interfaces, the ONU-ID previously assigned to the pilot PON interface, which has been activated first.
3	Message type ID	0x01, "Serial_Number_ONU"
4	SeqNo	Set to 0x00 for all instances of Serial_Number_ONU PLOAM message.
5-8	Vendor_ID	See clause 11.2.6.1.
9-12	VSSN	See clause 11.2.6.2.
13-16	Random_delay	The random delay used by the ONU when sending this message, expressed in time quanta.
17-18	Correlation tag	See clause 11.2.6.3.
19-22	Current downstream PON-ID	The PON-ID received by the ONU in its current downstream wavelength channel.
23-26	Current upstream PON-ID	The PON-ID of the Channel_Profile message containing the descriptor of the upstream wavelength channel in which the ONU is transmitting.
27-34	Calibration record status	See clause 11.2.6.4.
35	Tuning granularity	See clause 11.2.6.5.
36	One-step tuning time	See clause 11.2.6.6.

Table 11-25 – Serial_Number_ONU message

Octet	Content	Description
37	Upstream line rate capability	A bitmap of the form 0000 ABCL indicating the ONU's upstream nominal line rate capability: A – Upstream nominal line rate $\rho_0 \phi_0$ A = 0: not supported; A = 1: supported. B – Upstream nominal line rate $\rho_0 \phi_1$ B = 0: not supported; B = 1: supported. C – Upstream nominal line rate $\rho_0 \phi_2$ C = 0: not supported; C = 1: supported. L – reserved, set as 0 by transmitter.
38	Attenuation	See clause 11.2.6.7.
39	Power levelling capability	See clause 11.2.6.8.
40	Activation Debug information	The octet of the form DDDD RRCS. DDDD is the activation reason code that reflects the most recent transition to O2-3 state. The Activation reason code has the following code points: 0000 – activation debug is not supported, no previous operation history is available, or the ONU is in a factory-fresh configuration. 0001 – Deactivate_ONU-ID PLOAM has been received in O2-3; 0010 – Deactivate_ONU-ID PLOAM has been received in O4; 0011 – Deactivate_ONU-ID PLOAM has been received in another state (that is, a state with a functional OMCC); 0100 – Calibration_Request PLOAM has been received in O2-3; 0101 – the ONU is being enabled after Emergency Stop (that is, after a sojourn in O7 state); 0110 – LODS has occurred in O2-3; 0111 – LODS has occurred in O4; 1000 – TOZ has expired in O2-3; 1001 – TO1 has expired in O4; 1010 – TO2 has expired in O6; 1011 – TO4 has expired in O8; 1100 – TO5 has expired in O9; 1101 – ONU has lost power. Other code points reserved. C is channel change flag, which is set in connection with a non-zero value of the Activation reason code to indicate that the wavelength channel has been changed, and the new value was pre-determined by the PLOAM protocol. The C flag is persistent between activation attempts, and is cleared, once the OMCC is established.

Table 11-25 – Serial_Number_ONU message

Octet	Content	Description
		S is a scan flag which is set to indicate the current channel (which may or may not change from the previous activation) has been found in the course of wavelength channel scanning. The S flag is persistent between activation attempts, and is cleared, once the OMCC is established. R – reserved; ONU sets this bit to zero.
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.

11.3.4.2 Registration message

Information regarding Registration message is provided in Table 11-26.

Table 11-26 – Registration message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x02, "Registration".
4	SeqNo	Repeated from downstream Request_Registration message, or 0 if generated in response to a ranging grant in the Ranging state (O4).
5-40	Registration_ID	A string of 36 octets that has been assigned to the subscriber on the management level, entered into and stored in non-volatile storage at the ONU. Registration_ID may be useful in identifying a particular ONU installed at a particular location. The default is a string of 0x00 octets (Note).
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.
NOTE – It is recommended that the Registration_ID be a string of ASCII characters, justified in the lower-numbered bytes of the registration message, and with 0x00 values in unused byte positions.		

11.3.4.3 Key_Report message

Information regarding Key_Report message is provided in Table 11-27.

Table 11-27 – Key_Report message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x05, "Key_Report".
4	SeqNo	Repeats the value from the downstream Key_Control message. If the length of the keying material requires that several Key_Report messages be sent upstream, the sequence number is the same in each of them.
5	Report type	0000 000R R – Report type: R = 0: New key; R = 1: Report on existing key.

Table 11-27 – Key_Report message

Octet	Content	Description
6	Key index	0000 00BB, where: BB – Key index: 01: First key of a key pair; 10: Second key of a key pair.
7	Fragment number	0000 0FFF FFF: Three-bit fragment number, range 0..7. The first fragment is number 0. The last fragment may be partial, padded with 0x00 at the least significant end (Note).
8	Reserved	Set to 0x00 by the transmitter and treated as "don't care" by the receiver
9-40	Key_Fragment	Key fragment, 32 bytes. Any padding that may be required is in the higher-numbered bytes of the message. For a report on the existing key, a single fragment containing the key name is sent. Key_Name = BC_CMAC (KEK, encryption_key | 0x33313431353932363533353839373933, 128). For a new key, KEK_encrypted key is used. KEK_Encrypted_key = BC_ECB (KEK, encryption_key).
41-48	MIC	Message integrity check, computed using the ONU-specific derived shared PLOAM integrity key.
NOTE – This parameter supports the long-term extensibility of the data encryption key exchange protocol. The currently specified (see clause 15.4) 128- and 256-bit cryptographic methods for the data encryption (AES-128, AES-256, SM4, etc.) require a single key fragment and only one Key_Report PLOAM message to transmit the key.		

11.3.4.4 Acknowledgement message

Information regarding Acknowledgement message is provided in Table 11-28.

Table 11-28 – Acknowledgement message

Octet	Content	Description
1	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x09, "Acknowledgement".
4	SeqNo	Same as downstream sequence number. Set to the value of SeqNo in the downstream PLOAM message to which the present message provides an acknowledgement. If the ONU has no upstream message to send (keep-alive grant from OLT), it sets the upstream sequence number to 0x00. If the ONU has no upstream message to send, it treats a PLOAMu flag set by the OLT as a keep-alive grant, and generates the present message, setting the upstream sequence number to 0x00 and the Completion code to 0x01.

Table 11-28 – Acknowledgement message

Octet	Content	Description
5	Completion _code	Completion code: 0x00: OK; 0x01: No message to send; 0x02: Busy, preparing a response; 0x03: Unknown message type; 0x04: Parameter error; 0x05: Processing error. 0x06: Unsolicited indication of traffic activity. 0x07: Mode of operation not supported. Other values reserved.
6	Attenuation	See clause 11.2.6.7.
7	Power levelling capability	See clause 11.2.6.8.
8-9	Busy Alloc-ID	In response to an idle support contention-based allocation, a request for a directed allocation to the specified Alloc-ID, which has traffic for upstream transmission; LSB-justified within a two-octet field. Octet 8 set to 0xC0 indicates that all Alloc-IDs of the sender ONU require directed allocations. Set to 0x0000, otherwise.
10-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the ONU-specific derived shared PLOAM integrity key.

11.3.4.5 Sleep_Request message

Information regarding Sleep_Request message is provided in Table 11-29.

Table 11-29 – Sleep_Request message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x10, "Sleep_Request".
4	SeqNo	Always 0x00
5	Activity _level	Activity level: 0x00: Sleep_Request (Awake) 0x03: Sleep_Request (WSleep) Watchful sleep mode request: when in a LowPower state, the ONU periodically checks the downstream traffic for wake-up indications from the OLT CT. Other values reserved.
6-40	Padding	Set to 0x00 by the transmitter and treated as "don't care" by the receiver.
41-48	MIC	Message integrity check, computed using the ONU-specific derived shared PLOAM integrity key.

11.3.4.6 Tuning_Response message

The Tuning_Response PLOAM message is used in the process of ONU wavelength channel handover (see clause 17.3). Information regarding Tuning_Response message is provided in Table 11-30.

Table 11-30 – Tuning_Response message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender
3	Message type ID	0x1A, "Tuning_Response".
4	SeqNo	Eight-bit unicast PLOAM sequence number. Repeats the value from the downstream Tuning_Control PLOAM message. The same value is used in Tuning_Response(ACK) and subsequent Tuning_Response(Complete_u/ROLLBACK) messages. Note that in case of Tuning_Response(Complete_u), the OLT CT ignores this value.
5	Operation code	Operation code: 0x00: ACK; 0x01: NACK; 0x03: Complete_u; 0x04: ROLLBACK. Other values reserved.
6-7	Response code	Response code: 0x0000: As long as Operation code is ACK or Complete_u. Response codes reported with NACK operation code (see Table 17-3 in clause 17.3.2 for the explanation of failure conditions): 0x0001: INT_SFC; 0x0002: DS_ALBL; 0x0004: DS_VOID; 0x0008: DS_PART; 0x0010: DS_TUNR; 0x0020: DS_LNRT; 0x0040: DS_LNCD; 0x0080: US_ALBL; 0x0100: US_VOID; 0x0200: US_TUNR; 0x0400: US_CLBR; 0x0800: US_LKTP; 0x1000: US_LNRT; 0x2000: US_LNCD. Response codes reported with ROLLBACK operation code (see Table 17-4 in clause 17.3.2 for the explanation of failure conditions): 0x0001: COM_DS; 0x0002: DS_ALBL; 0x0004: DS_LKTP; 0x0008: US_ALBL; 0x0010: US_VOID;

Table 11-30 – Tuning_Response message

Octet	Content	Description
		0x0020: US_TUNR; 0x0040: US_LKTP; 0x0080: US_LNRT; 0x0100: US_LNCD. Other values reserved.
8-11	Vendor_ID	See clause 11.2.6.1.
12-15	VSSN	See clause 11.2.6.2.
16-17	Correlation tag	See clause 11.2.6.3.
18-21	PON-ID	The PON-ID received by the ONU in its current downstream wavelength channel.
22	UWLCH ID	An octet of the form 0000 UUUU, where: UUUU – the UWLCH ID of the upstream wavelength channel in which the ONU is transmitting.
23-30	Calibration record status	See clause 11.2.6.4.
31	Tuning granularity	See clause 11.2.6.5.
32	One-step tuning time	See clause 11.2.6.6.
33	Upstream line rate capability	An indicator of ONU's upstream nominal line rate capability of the form 0000 ABCL, where: A – Upstream nominal line rate $\rho_0 \phi_0$ A = 0: not supported; A = 1: supported. B – Upstream nominal line rate $\rho_0 \phi_1$ B = 0: not supported; B = 1: supported. C – Upstream nominal line rate $\rho_0 \phi_2$ C = 0: not supported; C = 1: supported. L – reserved, set as 0 by transmitter.
34	Attenuation	See clause 11.2.6.7.
35	Power levelling capability	See clause 11.2.6.8.
36-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.

11.3.4.7 Power_Consumption_Report message

Information regarding Power_Consumption_Report message is provided in Table 11-31.

Table 11-31 – Power_Consumption_Report message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x1B, "Power_Consumption_Report".
4	SeqNo	Same as downstream sequence number. Set to the value of SeqNo in the downstream Power_Consumption_Inquire PLOAM message to which the present message provides a response.
5-28	Power consumption	Power consumption containing a 16-bit indicator for each TWDM channel in the system. Packing and arrangement is: "DDDDUUUU XXXX XXXX XXXX XXXX" repeats 8 times, each one represents one downstream/upstream wavelength channel and its associated power consumption estimation information. DDDDUUUU – TWDM downstream/upstream wavelength channel; 0xFF represents the 16-bits reserved. XXXXXXXX XXXX XXXX – Power consumption of associated TWDM channel, with the unit of milliwatt (maximal value is 65.535W). 0x0000 represents the unknown power consumption of the associated TWDM channel. ONU should report its power consumption with the linear unit milliwatt (absolute power) or that with the same offset (relative power) for different channels to the OLT. It supports the ONU to report power consumption for eight channels in one message. ONUs can respond twice if power consumption for more than eight channels is reported.
29-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.

11.3.4.8 Bonded_Channel_Response message

Information regarding Bonded_Channel_Response message is provided in Table 11-32.

Table 11-32 – Bonded_Channel_Response message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x1D, "Bonded_Channel_Response".
4	SeqNo	Repeats sequence number of the corresponding downstream Bonded Channel Status message; or 0x00 if Unsolicited Channel Status Report
5	Opcode/Correlation ID	0x00: Channel Status report (either requested or unsolicited) Non zero code: Instruction Correlation ID being confirmed by the present PLOAM message

Table 11-32 – Bonded_Channel_Response message

Octet	Content	Description
6-13	Wavelength channel 1..8 status	Wavelength channel status: 0x00 – O5 Bonded 0x01 – O5 Suspended 0x04 – Out of O5, exact state cannot be determined 0x05 – No Light (O1.1) 0x06 – In activation (O1.2 through O4) 0x07 – ILODS (O6) 0x08 – Hardware failure 0xFF – Absent
14-40	Padding	Set to 0x00 by the transmitter; treated as "don't care" by the receiver.
41-48	MIC	Message integrity check computed using the default PLOAM integrity key.

11.3.4.9 ONU_Capabilities message

Information regarding ONU_Capabilities message is provided in Table 11-33.

Table 11-33 – ONU_Capabilities message

Octet	Content	Description
1-2	ONU-ID	ONU-ID of the message sender.
3	Message type ID	0x1E, "ONU_Capabilities".
4	SeqNo	Repeated from downstream Get_Set_Capabilities message.
5	Acknowledgement code	Completion code: 0x00: OK; 0x01: Unsupported feature requested; Other values reserved by ITU-T. When the Get_Set_Capabilities PLOAMd message has 'Query/Set' bit S = 0, ONU responds with completion code 0x00 (OK). When the Get_Set_Capabilities PLOAMd message has 'Query/Set' bit S = 1, ONU responds with completion code 0x01 (Unsupported feature requested).
6-40	Capabilities	0x00: No support for future capabilities. Other values reserved by ITU-T.
41-48	MIC	Message integrity check, computed using the ONU-specific derived shared PLOAM integrity key.

11.4 PLOAM message operation categories

PLOAM messages defined in clause 11.3 can be classified into two categories:

– PLOAM messages for general operation, see Table 11-34;

– PLOAM messages for multiple wavelength opearion, see Table 11-35.

Table 11-34 – PLOAM messages for general operation

Categoty	Major functions	Downstream PLOAM messages	Upstream PLOAM messages	Required hardware capabilities
General operation	Profile/ capability announcement	Burst_Profile; Get_Set_Capabilities	Acknowledgement; ONU_Capabilities	Functions are logical link layer related; No requirement to transceiver
	ONU activation	Assign_ONU-ID/ Collision_Feedback; Ranging_Time; Deactivate_ONU-ID; Disable_Serial_Number; Reboot_ONU	Serial_Number_ ONU	
	ONU registration	Request_Registration	Registration	
	Encryption key control	Key_Control	Key_Report	
	Power management	Sleep_Allow	Sleep_Request	
	Power levelling	Change_Power_Level	Serial_Number_ONU; Acknowledgement	If an ONU needs to support power levelling, its transmitter should calibrate several launch power levels

Table 11-35 – PLOAM messages for multiple wavelength operation

Categoty	Major functions	Downstream PLOAM messages	Upstream PLOAM messages	Required hardware capabilities
Multiple wavelength operation	Profile announcement	System_Profile; Channel_Profile		An ONU only needs to listen.
	Protection switching	Protection_Control		An ONU needs to support multiple channels or wavelength channel tuning.
	ONU wavelength channel bonding	Bonded_Channel_Status	Bonded_Channel_Response	An ONU needs to support multiple channels and channel bonding.

Table 11-35 – PLOAM messages for multiple wavelength operation

Categoty	Major functions	Downstream PLOAM messages	Upstream PLOAM messages	Required hardware capabilities
	ONU wavelength channel handover	Tuning_Control	Tuning_Response	An ONU needs to support multiple channels. It also needs to support channel control.
	Power management	Power _Consumption _Inquire	Power _Consumption _Report	An ONU needs to monitor power consumption of different channels.
	Wavelength calibration	Calibration_ Request Adjust_ Tx_Wavelength		An ONU needs to support wavelength fine tuning.

12 ONU activation cycle

12.1 Overview

This clause specifies the ComTC layer behaviour of an ONU using a state machine. The unique state of this state machine that an ONU enters upon powering up is referred to as Initial state. An ONU may re-enter the Initial state under certain specified conditions. An evolution of the ONU state between two consecutive re-entries into the Initial state is known as an *activation cycle*, and the state machine itself is referred to as *the ONU activation cycle state machine*. As a matter of convenience, the ONU activation cycle state machine can be partitioned into two blocks: (1) activation proper, and (2) operation.

12.2 Activation outline

The activation proper includes three phases: downstream synchronization, serial number acquisition (ONU discovery), and ranging.

During the downstream synchronization phase, the ONU, while remaining passive, initializes a local instance of the downstream synchronization state machine, attains synchronization to the downstream signal, and starts learning system, channel, and burst profile parameters. In a TWDM system, the ONU may repeat the process for two or more available downstream wavelength channels, and may create and store the calibration record for those channels. The phase concludes with the ONU selecting one downstream wavelength channel to proceed with activation.

During the serial number acquisition/ONU discovery phase, the ONU, while continuing to collect the system, channel, and burst profile parameters, enables its transmitter and announces its presence on the PON by responding to serial number grants. In a TWDM system, if necessary, the OLT CT instructs the ONU to adjust its transmitter wavelength to the desired upstream wavelength channel or to resume activation at a different downstream wavelength channel. In a TWDM system, the ONU may create and store the calibration record for the upstream wavelength channel. The phase concludes when the OLT CT, which has discovered the new ONU by its serial number assigns a unique ONU-ID to the ONU.

During the ranging phase, the ONU responds to directed ranging grants. The phase concludes when the OLT CT completes the round-trip delay measurements, computes the equalization delay, and communicates the equalization delay to the ONU.

Note that when a dedicated activation wavelength is introduced to eliminate quiet window during activation, the above three phases are conducted in the activation wavelength channel. See Appendix IX for the details of quiet window elimination in ONU activation.

12.3 Causal sequence of activation events

The OLT CT controls the ONU activation by means of issuing serial number and ranging grants and exchanging upstream and downstream PLOAM messages. The outline of the activation events in their causal order is given below:

– The activating ONU attains PSync and superframe synchronization and collects the ComTC-layer protocol version and burst profile information. In a TWDM system, before attaining synchronization, the ONU tunes its receiver to search for a downstream wavelength channel. A TWDM ONU also collects the system and channel information, confirming the Tx parameters, the channel partition, and the upstream line rate match those of the ONU. The TWDM ONU may repeat the downstream wavelength channel search as necessary. Actions to take upon a mismatch between the OLT CT and ONU ComTC-layer version are implementation specific.

– The ONU starts responding to the serial number grants, announcing its presence on the PON with a Serial_Number_ONU PLOAM message responding to serial number grants with rate-dependent broadcast Alloc_ID (see Table 6-2). The ONU may exercise power levelling if capable of doing so. The Serial_Number_ONU PLOAM message declares the ONU's serial number and the random delay used for transmission. In a TWDM system, the ONU makes best effort to tune its transmitter to the upstream wavelength channel ID (specified by the Channel_Profile message). In a TWDM system, the Serial_Number_ONU PLOAM message in addition reports the selected downstream wavelength channel, the calibration record status, and the tuning/dithering capabilities. It also contains the Correlation tag field which allows the ONU to associate OLT CT's feedback in the form of Calibration_Request or Adjust_Tx_Wavelength PLOAM message with the specific transmitted message.

– When the OLT CT discovers the serial number of a newly connected ONU, it may assign an ONU-ID to the ONU using the Assign_ONU-ID PLOAM message. In a TWDM system, the OLT CT may assist the ONU in tuning its transmitter to the desired upstream wavelength channel with Adjust_Tx_Wavelength PLOAM message, or request that ONU calibrate another wavelength channel with Calibration_Request PLOAM message.

– The OLT CT optionally issues a directed ranging grant to a newly discovered ONU and prepares to accurately measure the response time.

– The ONU responds to a directed ranging grant with the Registration PLOAM message.

– The OLT CT optionally performs initial authentication of the ONU based on the Registration_ID, computes the individual equalization delay, and communicates this equalization delay to the ONU using the Ranging_Time PLOAM message.

– The ONU adjusts the start of its upstream PHY frame clock based on its assigned equalization delay.

– The ONU completes activation and starts operation.

For the ONUs in operation, the OLT CT monitors the received signal strength indication (RSSI), the phase, and the BER of the arriving upstream transmissions. Based on the monitored information, the OLT CT may re-compute and dynamically update the equalization delay for any ONU. In a TWDM system, the OLT CT may instruct the ONU to perform upstream wavelength adjustment if the ONU is capable of doing so.

12.4 ONU activation cycle state machine

12.4.1 States, timers, and inputs

Table 12-1 summarizes the ONU activation cycle states.

Table 12-1 – ONU activation cycle states

ONU State/Substate		Semantics
Ref	**Full name**	
O1	Initial state	The ONU enters the Initial state (O1) when it originally powers up, remaining in this state in the course of downstream channel scanning and calibration, and may re-enter this state during the operation, for example, when being deactivated, or when being enabled after an emergency stop. The transmitter is off. Upon entry to O1 state, the ONU-ID, default and explicitly assigned Alloc-IDs, default XGEM Port-ID, burst profiles, and equalization delay should be discarded. The ONU synchronization state machine (see clause 10.1.3) is initialized.
	O1/Off-Sync ≡ O1.1	The substate is the entry point to O1 state. The ONU searches for and attempts to synchronize to a downstream signal. Once the downstream synchronization is attained, the ONU transitions to the O1/Profile Learning substate. In TWDM, if the downstream wavelength channel to which the ONU attains synchronization is different from the one where the system and channel profile information has been collected, the ONU discards the system and channel profile information. In TWDM, the ONU may create and store a calibration record for the downstream wavelength channel.
	O1/Profile Learning ≡ O1.2	The ONU starts the TProfileDwell timer, whose initial value shall be at least 10 s. The ONU parses the PLOAM partition of downstream FS frames and starts collecting system, channel, and burst profile information. Once sufficient information is collected, the ONU performs the downstream wavelength channel evaluation (see Internal events of Table 12-3). If the present downstream wavelength channel is suitable for activation then the ONU proceeds with activation and transitions to O2-3 state. In TWDM, if the present downstream wavelength channel is unsuitable for activation then the ONU searches for an alternative downstream wavelength channel, it returns to the O1/Off-Sync substate, retaining the system and channel profile information, but discarding the burst profile information. If timer TProfileDwell expires without sufficient profile information having being collected for evaluation, the ONU abandons the current wavelength channel, returns to the O1/Off-Sync substate, and searches for an alternative downstream wavelength channel.

Table 12-1 – ONU activation cycle states

ONU State/Substate		Semantics
Ref	**Full name**	
O2-3	Serial Number state	The ONU starts the discovery timer TOZ. The ONU activates its transmitter. Once the ONU receives a serial number grant, it responds with a Serial_Number_ONU PLOAM message. The ONU awaits for and acts upon the discovery feedback from the OLT CT in the form of Assign_ONU-ID, and transitions to O4 state to continue activation. In TWDM, the ONU also makes best effort to tune it to the upstream wavelength channel corresponding to the host downstream wavelength channel. Once an ONU which satisfies the minimum calibration accuracy requirement for the desired upstream wavelength channel receives a serial number grant, it responds with a Serial_Number_ONU PLOAM message. The ONU awaits for and acts upon the discovery feedback from the OLT CT, which can be in the form of Assign_ONU-ID, Calibration_Request, or Adjust_Tx_Wavelength PLOAM messages. Depending upon the feedback, the ONU either stays in O2-3 state while retuning the transmitter, or returns to O1 state in order to calibrate another TWDM channel, or transitions to O4 state to continue activation. Upon receiving the OLT CT feedback, the ONU may create and store a calibration record for the upstream wavelength channel. In TWDM, if the ONU supports power levelling, it may exercise the ONU-activated power levelling while responding to the serial number grants with the Serial_Number_ONU messages. If the discovery timer TOZ expires without the ONU receiving the feedback from the OLT CT, the ONU abandons the host wavelength channel and returns to O1 state to search for an alternative downstream wavelength channel. In this case the ONU discards any collected system, channel, and burst profile information.
O4	Ranging state	The ONU starts ranging timer TO1. While awaiting the assignment of equalization delay by the OLT CT, the ONU responds to the directed ranging grants. If the ONU receives a ranging grant with a burst profile known from a previously received Burst_Profile PLOAM message, it transmits an FS burst carrying a Registration PLOAM message. The ONU ignores the values of the DBRu flag and GrantSize field of the ranging grant allocation structure. Once the ONU receives the Ranging_Time message with absolute equalization delay, it transitions to the Operation state (O5). If timer TO1 expires, the ONU discards the assigned ONU-ID value along with default Alloc-ID and default OMCC XGEM port-ID and transitions to the Serial Number state (O2-3), while keeping the collected profile information.
O5	Operation state	The ONU processes downstream frames and transmits upstream bursts, as directed by the OLT CT, to the full extent of the present specification. Upon entry to state O5, the ONU starts timer TO6, and restarts it in each PHY frame in which it receives an upstream allocation. Upon timer TO6 expiration, the ONU transitions to the Initial state (O1). The ONU stops timer TO6 when it leaves state O5.
	O5/Associated ≡ O5.1	This substate is the entry point to O5 state. The upstream SDU fragmentation rules are applicable without additional restrictions. In TWDM, the ONU is associated with a specific TWDM channel, and no Tuning_Control PLOAM message is pending execution.

Table 12-1 – ONU activation cycle states

ONU State/Substate		Semantics
Ref	**Full name**	
	O5/Pending ≡ O5.2	In TWDM, the ONU has received and acknowledged a Tuning_Control PLOAM message. The target downstream and upstream wavelength channels are recorded, as is the Scheduled SFC. The latter is a 16-bit value used to generate an internal event to trigger the tuning procedure. While in the O5/Pending substate, the ONU completes upstream transmission of the SDUs whose fragmentations started while in the O5/Associated substate, applying additional fragmentation, if necessary, and transmits any whole (unfragmented) SDUs. However, the ONU does not start fragmentation of any new SDUs. If the SDU size exceeds the available FS payload, the idle XGEM frames shall be transmitted.
O6	Intermittent LODS state	The ONU enters this state from either substate of the Operation state (O5) following the loss of downstream synchronization. Upon entry to the Intermittent LODS state (O6), the ONU starts timer TO3 if the wavelength channel protection (WLCP) is ON, or timer TO2 if WLCP is OFF. If the downstream signal is re-acquired before timer TO2 or timer TO3 expires, the ONU transitions back into the Operation state (O5). Upon timer TO2 expiration, the ONU transitions to the Initial state (O1), upon timer TO3 expiration, the ONU transitions to the Downstream Tuning state (O8).
O7	Emergency Stop state	If an ONU receives a Disable_Serial_Number message with the 'disable' option (pertaining to the given ONU as specified by the Disable/Enable parameter of the message), it switches its laser off and transitions to the Emergency Stop state (O7). When in the Emergency Stop state (O7), the ONU keeps the downstream synchronization state machine running and parses the PLOAM partition of downstream FS frames, but is prohibited from forwarding data in the downstream direction or sending data in the upstream direction. If while in the Emergency Stop state (O7), the ONU loses the downstream synchronization, it retunes its receiver to find an alternative downstream wavelength channel, starting with preconfigured protection channel, if any. If the ONU in the O7 state receives a Disable_Serial_Number message with the 'enable' option, it transitions to the Initial state (O1). The Emergency Stop state (O7) persists over ONU reboot and power cycle.
O8	Downstream Tuning state	In TWDM, the ONU starts downstream tuning timer TO4. The ONU attempts to resume operation in a new TWDM channel, while retaining its ComTC layer configuration, including the burst profiles as long as the system supports the advance burst profile distribution. Contingent on the specific wavelength management scenario, the new TWDM channel can be the target channel of the wavelength tuning operation, the previous working channel in case of tuning operation rollback, the preconfigured protection channel, or any available TWDM channel with matching parameters. If timer TO4 expires while the ONU is in either substate of the Downstream Tuning state (O8), the ONU transitions to the Initial state (O1) discarding the ComTC layer configuration.
	O8/Off-Sync ≡ O8.1	This substate is the entry point to O8 state. The ONU tunes its receiver attempting to synchronize to the downstream signal. The ONU may also tune its transmitter. Once the downstream synchronization is attained, the ONU transitions to the O8/Profile Learning substate.

Table 12-1 – ONU activation cycle states

ONU State/Substate		Semantics
Ref	**Full name**	
	O8/Profile Learning ≡ O8.2	The ONU parses the PLOAM partition of downstream FS frames and collects system, channel, and burst profile information. The previously accumulated system, channel, and burst profile information may be accepted as valid, unless the corresponding profile version has changed. Once sufficient information is collected to perform the downstream wavelength channel evaluation, the ONU makes a decision to either continue using the present downstream wavelength channel as a host, or to search for an alternative downstream wavelength channel. If the ONU decides to continue using the host downstream wavelength channel, it transitions to O9 state. If the ONU decides to search for an alternative downstream wavelength channel, it returns to the O8/Off-Sync substate, discarding the burst profile information.
O9	Upstream Tuning state	In TWDM, the ONU starts upstream tuning timer TO5, whose initial value depends on whether the ONU is calibrated for the response, and completes its transmitter tuning. Once the ONU receives an applicable PLOAM grant, it transmits an appropriate upstream PLOAM message, contingent upon the specific wavelength management scenario: Tuning_Response(Complete_u) in case of target TWDM channel or preconfigured TWDM channel, Tuning_Response(Rollback) in case of previous working channel after failed tuning. The ONU ignores the values of the DBRu flag and GrantSize field the directed PLOAM grant allocation structure. The ONU transmits Tuning_Response(Complete_u) PLOAM messages in response to each directed PLOAM grant or a broadcast contention-based wavelength protection grant, available under a collision resolution protocol, until feedback from the OLT CT is received, or timer TO5 expires. If the ONU supports power levelling, it may exercise the ONU-activated power levelling while responding to the directed PLOAM grants with the Tuning_Response PLOAM messages. The ONU awaits for and acts upon the upstream tuning feedback from the OLT CT, either staying in the Upstream Tuning state (O9) while fine-tuning the transmitter, or completing upstream tuning and resuming normal operation in the Operation state (O5), or, if timer TO5 expires, discarding the ComTC layer configuration and returning to the Initial state (O1).

Table 12-2 summarizes the ONU activation cycle state machine timers.

Table 12-2 – ONU activation cycle state machine timers

Timer	Full name	State	Semantics and initial value
TOZ	Discovery timer	O2-3	Timer TOZ controls the duration of an ONU discovery attempt in the Serial Number state (O2-3), forcing a transition to the Initial state (O1) if the discovery feedback from the OLT CT is lacking. If the ONU is calibrated for the response, the recommended initial value of timer TOZ is 20 seconds.
TO1	Ranging timer	O4	Timer TO1 is used to abort an unsuccessful activation attempt by limiting the overall time an ONU can remain in the Ranging state (O4). The recommended initial value of timer TO1 is 10 seconds.

Table 12-2 – ONU activation cycle state machine timers

Timer	Full name	State	Semantics and initial value
TO2	Loss of downstream synchronization (LODS) timer.	O6	Timer TO2 is used to assert a failure to recover from an intermittent LODS condition by limiting the time an ONU can remain in the Intermittent LODS state (O6).
TO3	LODS protection timer	O6	Timer TO3 is used to initiate wavelength channel protection handover in the Intermittent LODS state (O6). TO3 is effectively set to infinity in the TDM operation mode.
TO4	Downstream tuning timer	O8	Timer TO4 is used to abort an unsuccessful wavelength channel tuning operation in O8 state, when no suitable downstream wavelength channel is found.
TO5	Upstream tuning timer	O9	Timer TO5 controls the duration of an upstream wavelength channel tuning attempt in O9 state, forcing a transition to the Initial state (O1) if the upstream tuning feedback from the OLT CT is lacking.
TO6	Forgotten ONU timer	O5	Timer TO6 allows an ONU that accidentally remains in O5 state while no longer being accounted for by the OLT CT to reactivate itself. The initial value of timer TO6, which is set autonomously by the ONU, must be 10 s.

The Applicable states column in Table 12-3 includes all states where the event may occur in principle, including due to protocol error. Whether an event requires processing is indicated in Table 12-4.

Table 12-3 – ONU activation cycle state machine inputs

Input	Applicable states	Semantics
Downstream synchronization events		
DSYNC	O1/Off-Sync; O6; O8/Off-Sync.	Downstream synchronization attained. The event is generated by the downstream synchronization state machine upon transition from the Pre-Sync state to the Sync state.
LODS	All states and substates, except O1/Off-Sync; O6; O8/Off-Sync.	Loss of downstream synchronization. The event is generated by the downstream synchronization state machine upon transition from the Re-Sync state to the Hunt state.
Internal events		
SFC match	O5/Pending	The recorded Scheduled SFC value matches the 16 least significant bits of the locally maintained SFC copied from the PSBd structure of the downstream PHY frame. In TWDM, the event is qualified by whether the tuning operation involves the receiver or the transmitter only. Using the local copy of the SFC allows to recognize the SFC match event even when the downstream synchronization state machine is in the Re-Sync state (i.e., no valid downstream PHY frame is delineated).
DWLCH ok to work	O1/Profile Learning; O8/Profile Learning	Result of the internal system and channel profile evaluation: the channel partition, upstream optical link type and the upstream line rate match those of the ONU, the appropriate activation option for the current calibration accuracy is available, and the wavelength channel deemed suitable for activation.

Table 12-3 – ONU activation cycle state machine inputs

Input	Applicable states	Semantics
DWLCH not appropriate	O1/Profile Learning; O8/Profile Learning	Result of the internal system and channel profile evaluation: either the channel partition, upstream optical link type or the upstream line rate do not match those of the ONU, the appropriate activation option for the given calibration accuracy is not available, or the wavelength channel deemed unsuitable for activation.
Timer events		
TOZ expires	O2-3	Timer expiration.
TO1 expires	O4	Timer expiration.
TO2 expires	O6	Timer expiration.
TO3 expires	O6	Timer expiration. Recognized in TWDM operation mode only.
TO4 expires	O8	Timer expiration. Recognized in TWDM operation mode only.
TO5 expires	O9	Timer expiration. Recognized in TWDM operation mode only.
TO6 expires	O5	Timer expiration.
BWmap events		
SN grant	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	An SN grant is an allocation to one of the specified broadcast Alloc-IDs with a known burst profile, specific StartTime and the PLOAMu flag set. An ONU in the Serial Number state (O2-3) recognizes an SN grant event when it receives an SN grant with known burst profile. In TWDM, given the desired upstream wavelength channel, an ONU qualifies itself whether it is calibrated to that channel with sufficient or loose accuracy, or remains uncalibrated.
Directed PLOAM grant	O4, O5, O7, O8/Profile Learning, O9	An allocation to one of the ONU's Alloc-IDs with a known burst profile and PLOAMu flag set. A PLOAM grant is an allocation with the StartTime and GrantSize within their respective ranges (see clause 8.1.3). An ONU in O4 state interprets a PLOAM allocation to the default Alloc-ID as a ranging grant.
Data grant	O4, O5, O7, O8/Profile Learning, O9	An allocation to one of the ONU's Alloc-IDs with a known burst profile and non-zero GrantSize.
PLOAM events		
ONU-ID Assignment	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Broadcast Assign_ONU-ID PLOAM message with matching SN, matching ONU-ID, or both is received.
EqD Assignment	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Directed Ranging_Time PLOAM message with absolute delay specification is received
Deactivate ONU-ID request	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Deactivate_ONU-ID PLOAM message received (broadcast in O2-3state, either directed or broadcast in other states)
Disable SN request	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Disable_Serial_Number PLOAM message with Disable option received (Disable All, Disable specific SN, or Disable_Discovery options in O2-3 state, Disable All, Disable specific SN options in other states).

Table 12-3 – ONU activation cycle state machine inputs

Input	Applicable states	Semantics
Enable SN request	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Disable_Serial_Number PLOAM message with Enable option received (broadcast or SN-specific).
Calibration request	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Calibration_Request PLOAM message received. This event is only recognized in the TWDM operation mode.
Tuning request	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Tuning_Control PLOAM messages received with the request to tune the ONU to the specified pair of target downstream and target upstream wavelength channels at Scheduled SFC value. This event is only recognized in the TWDM operation mode.
US Tuning confirmation	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	Tuning_Control PLOAM messages with confirmation of the upstream wavelength tuning completion (Complete_d operation code), or a directed PLOAM message of any of the following types: Request_Registration, Assign_Alloc-ID, Key_Control, Sleep_Allow. This event is only recognized in the TWDM operation mode.
Other PLOAM messages*		
System_Profile	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	PLOAM message of specific type is received.
Channel_Profile	same as above	PLOAM message of specific type is received.
Burst_Profile	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	PLOAM message of specific type is received.
Ranging_Time (relative adjustment)	same as above	Either directed or broadcast Ranging_Time PLOAM message with relative delay specification is received.
Request_Registration	same as above	PLOAM message of specific type is received.
Assign_Alloc-ID	same as above	PLOAM message of specific type is received.
Key_Control	same as above	PLOAM message of specific type is received.
Sleep_Allow	same as above	PLOAM message of specific type is received.
Adust_Tx_Wavelength	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	PLOAM message of specific type is received.
Protection_Control	O1/Profile Learning, O8/Profile Learning, O2-3, O4, O5, O7, O9	PLOAM message of specific type is received.
* Although the input events of this part do not drive the ONU state machine, their effect depends on the ONU state at the time the event occurs (the message is received).		

12.4.2 ONU state diagram

The ONU activation cycle state transition diagram in the general case of the TWDM operation mode is graphically represented in Figure 12-1.

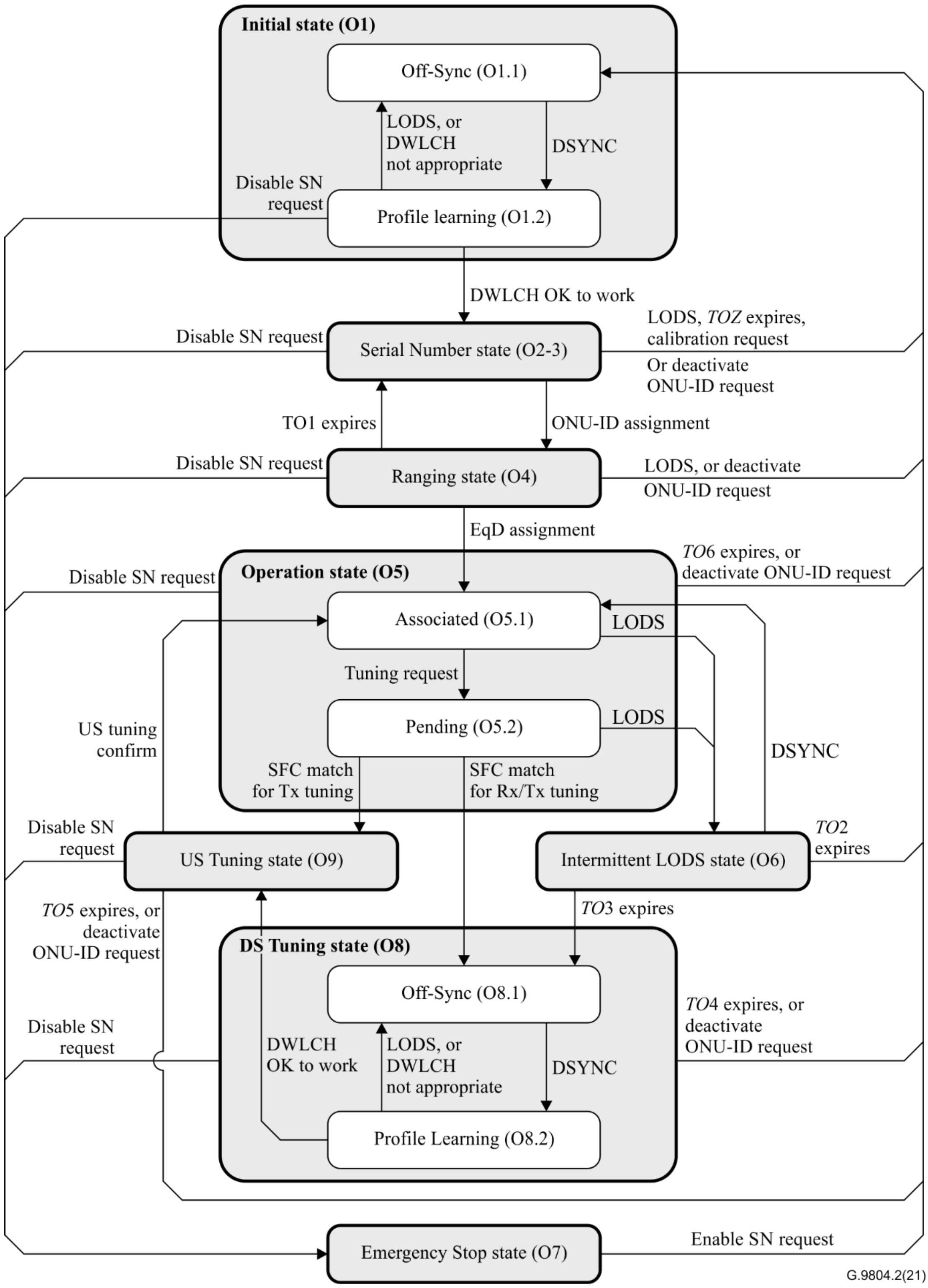


Figure 12-1 – ONU state diagram in TWDM operation mode

The simplified ONU activation cycle state transition diagram of the TDM operation mode involving single wavelength channel pair is graphically represented in Figure 12-2. Note that in the TDM operation mode the O5/Associated substate (O5.1) is essenciaitely the Operation state (O5).

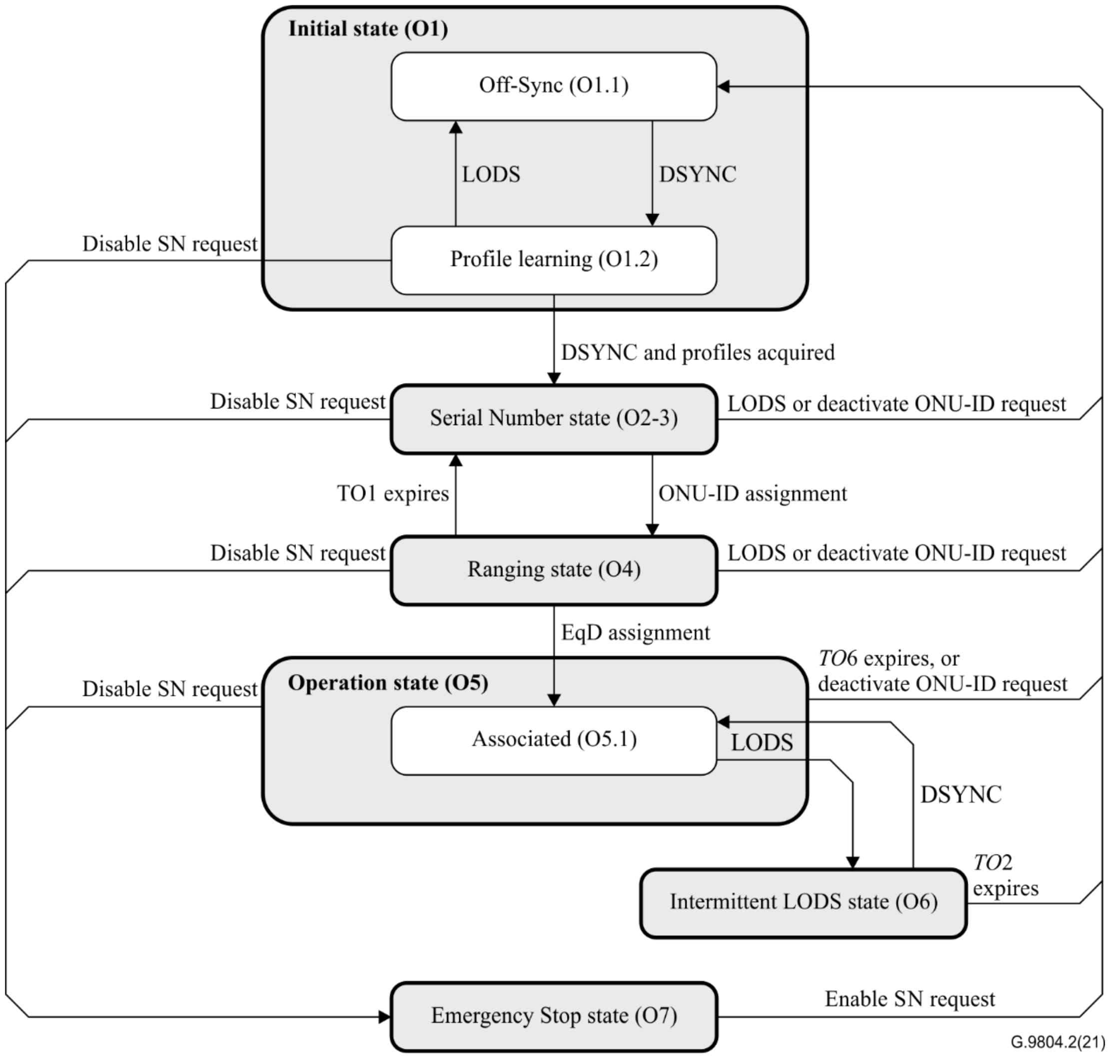


Figure 12-2 –ONU state diagram in TDM operation mode

12.4.3 ONU state transition table

Table 12-4 is more detailed than the state diagram of clause 12.4.2. In Table 12-4 a shaded cell indicates that an event is not applicable in the given state; a dash within a cell indicates that the event is not processed (ignored) in the given state. For the receipt of the PLOAM messages that do not drive the ONU activation cycle state machine, Table 12-4 only indicates whether the event is processed (plus) or ignored (dash) in the given state. The specific effects of the PLOAM message receipt are discussed in the corresponding clauses of this Recommendation. The ComTC layer configuration parameter sets referenced in Table 12-4 are specified in Table 12-5.

Table 12-4 – ONU activation cycle state transition table

Events	**ONU activation cycle states**										
	Initial state O1		**Serial Number state O2-3**	**Ranging state O4**	**Operation state O5**		**Intermittent LODS state O6**	**Emergency Stop state O7**	**Downstream Tuning state O8**		**Upstream Tuning state O9**
	Off-Sync O1.1	**Profile Learning O1.2**			**Associated O5.1**	**Pending O5.2**			**Off-Sync O8.1**	**Profile Learning O8.2**	
Power up If last operational state was O7 ==> O7 else ==> O1.1											
Downstream synchronization attained DSYNC	If DWLCH ID has changed, Discard VII; ==> O1.2;						Stop TO2/TO3; ==> O5.1;		==> O8.2;		
Loss of downstream synchronization LODS		Discard I; ==> O1.1;	Discard I; Stop TOZ; ==> O1.1;	Discard III; ==> O1.1;	**if** WLCP ON { Start TO3;} **else** { Start TO2; } Stop TO6; ==> O6;	**if** WLCP ON { Start TO3;} **else** { Start TO2; } Stop TO6; ==> O6;		–		Discard I; ==> O8.1;	–
SFC match; Rx only or Rx and Tx tuning						Stop TO6; Start TO4; Discard I; ==> O8.1;					
SFC match; Tx only tuning						Stop TO6; Start TO5; ==> O9;					
Downstream wavelength channel is OK to work		Start TOZ; ==> O2-3								Stop TO4; Start TO5; ==> O9	
Downstream wavelength channel is not appropriate		Discard I; ==> O1.1;								Discard I; ==> O8.1;	

Table 12-4 – ONU activation cycle state transition table

Events	ONU activation cycle states										
	Initial state O1		Serial Number state O2-3	Ranging state O4	Operation state O5		Intermittent LODS state O6	Emergency Stop state O7	Downstream Tuning state O8		Upstream Tuning state O9
	Off-Sync O1.1	Profile Learning O1.2			Associated O5.1	Pending O5.2			Off-Sync O8.1	Profile Learning O8.2	
Timer TOZ expires			Discard I; ==> O1.1;								
Timer TO1 expires				Discard II; Start TOZ; ==> O2-3;							
Timer TO2 expires							{Discard V; ==> O1.1;}				
Timer TO3 expires							{ Discard I; Start TO4; ==> O8.1; }				
Timer TO4 expires									Discard V; ==> O1.1;		
Timer TO5 expires											Discard V; ==> O1.1;
Timer T06 expires					{Discard V; ==> O1.1}						
SN grant		–	**if** RSSImin<RSSI< RSSImax, send SN_ONU PLOAM;	–	–	–		–		–	–
Directed PLOAM grant				Send Registration PLOAM;	Restart TO6; Send PLOAM message as required by general PLOAM protocol;			–		–	Send appropriate Tuning_ Response PLOAM
Data grant				–	Restart TO6; Send data, unrestricted fragmentation	Restart TO6; Send data, fragmentation restricted		–		–	–

Table 12-4 – ONU activation cycle state transition table

Events	ONU activation cycle states										
	Initial state O1		**Serial Number state O2-3**	**Ranging state O4**	**Operation state O5**		**Intermittent LODS state O6**	**Emergency Stop state O7**	**Downstream Tuning state O8**		**Upstream Tuning state O9**
	Off-Sync O1.1	**Profile Learning O1.2**			**Associated O5.1**	**Pending O5.2**			**Off-Sync O8.1**	**Profile Learning O8.2**	
ONU-ID assignment (Note 2)		–	Set II; Stop TOZ; Start TO1; ==> O4;	**if** ONU-ID consistent, Ignore; **else** **{**Discard III; Stop TO1; ==> O1.1;}	**if** ONU-ID consistent, {Restart TO6; Ignore ONU-ID assignment;} **else** **{** Stop TO6; Discard V; ==> O1.1;}			–		**if** ONU-ID consistent, Ignore; **else** **{**Discard V; Stop TO4; ==> O1.1;}	**if** ONU-ID consistent, Ignore; **else** **{**Discard V; Stop TO5; ==> O1.1;}
EqD assignment		–	–	{ Stop TO1; Set IV; Send ACK; ==> O5; }	{ Restart TO6; Set IV; Send ACK;}			–		Set IV;	Set IV;
Directed deactivate ONU-ID request		–	–	Discard III; Stop TO1; ==> O1.1;	Stop TO6; Discard V; ==> O1.1;			–		Discard V; Stop TO4; ==> O1.1;	Discard V; Stop TO5; ==> O1.1;
Broadcast deactivate ONU-ID request		–	Discard I; Stop TOZ; ==> O1.1;	Discard III; Stop TO1; ==> O1.1;	Stop TO6 Discard V; ==> O1.1;			–		Discard V; Stop TO4; ==> O1.1;	Discard V; Stop TO5; ==> O1.1;
Disable SN request		==> O7;	Stop TOZ; ==> O7;	Stop TO1; ==> O7;	Stop TO6; ==> O7;	Stop TO6; ==> O7;		–		Stop TO4; ==> O7;	Stop TO5; ==> O7;
Enable SN request		–	–	–	–	–		Discard VI; ==> O1.1		–	–
Calibration request		–	**if** current DWLCH, Start TOZ; **else {** Stop TOZ; ==> O1.1 }	–	–	–		–		–	–
Tuning request		–	–	–	Restart TO6; **if** accepted,	–		–		–	–

Table 12-4 – ONU activation cycle state transition table

Events	**ONU activation cycle states**										
	Initial state O1		**Serial Number state O2-3**	**Ranging state O4**	**Operation state O5**		**Intermittent LODS state O6**	**Emergency Stop state O7**	**Downstream Tuning state O8**		**Upstream Tuning state O9**
	Off-Sync O1.1	**Profile Learning O1.2**			**Associated O5.1**	**Pending O5.2**			**Off-Sync O8.1**	**Profile Learning O8.2**	
					{Send ACK; ==> O5.2} **else** Send NACK;						
US Tuning confirmation		–	–	–	–	–		–		–	Stop TO5; ==> O5;
System_Profile		+	+	+	+			–		+	+
Channel_Profile		+	+	+	+			–		+	+
Burst_Profile		+	+	+	+			–		+	+
Ranging_Time (relative adjustment)		–	–	–	+			–		+	+
Request_ Registration		–	–	–	+			–		–	+ (Note 1)
Assign_Alloc-ID		–	–	–	+			–		–	+ (Note 1)
Key_Control		–	–	–	+			–		–	+ (Note 1)
Sleep_Allow		–	–	–	+			–		–	+ (Note 1)
Adjust_ Tx_Wavelength		–	+	+	+			–		–	+
Protection_ Control		–	–	–	+			–		–	+ (Note 1)
Power _Consumption _Inquire		–	–	–	+			–		–	+ (Note 1)

NOTE 1 – The receipt of this message in the Upstream Tuning state (O9) defines an US Tuning confirmation event, causing a transition into Operation state (O5).

NOTE 2 – An ONU with previously assigned ONU-ID that has recognized ONU-ID assignment event considers the new assignment consistent if and only if both SN and ONU-ID match those of its own.

The composition of the ComTC layer configuration parameter sets referenced in Table 12-4 is specified in Table 12-5 below. The ONU's CPI does not belong to any of the specified sets, and is not subject to automatic discard on a transition of the ONU activation cycle state machine.

Table 12-5 – Reference ComTC layer configuration parameter sets

ComTC layer configuration item	Parameter set						
	I	II	III	IV	V	VI	VII
System profile parameters						X	X
Channel profile parameters						X	X
Burst profile parameters	X		X		X	X	
ONU-ID		X	X		X	X	
Default Alloc-ID		X	X		X	X	
Default XGEM Port-ID		X	X		X	X	
Assigned Alloc-IDs					X	X	
Equalization delay				X	X	X	
MSK and derived shared keys						X	
Protection PON-IDs						X	

Note that upon transition to state O1.1, along with discarding the appropriate ComTC layer configuration parameter set, the ONU shall discard any content from the PLOAM transmit queue.

12.5 OLT support of ONU activation

To allow ONUs to join or resume operations on the PON, the OLT CT regularly issues serial number grants.

A serial number grant is an allocation structure that is addressed to a broadcast Alloc-ID, carries a commonly known broadcast burst profile, and has the PLOAMu flag set. The serial number grants should have the DBRu flag reset, carry the GrantSize of 0 and be accompanied by an appropriate quiet window.

The frequency of serial number grants can be modulated by operational considerations, including pending ONU installations and the knowledge of temporarily inactive or failed ONUs.

Once the OLT CT receives a Serial_Number_ONU message from an ONU that is willing to join or resume operations on the PON, it checks the downstream PON-ID reported by the ONU. If the PON-ID is unexpected, then the OLT CT uses the ICTP to resolve the issue. If the PON-ID contains the expected administrative label and downstream wavelength channel ID, the OLT CT performs ONU-ID assignment and may issue directed ranging grants to that ONU in order to measure its round-trip delay.

If the OLT CT already knows the ONU, for example, from prior knowledge (e.g., for ONUs returning to the PON during recovery from loss of power) or by obtaining the ONU's Serial Number from another channel (e.g., dedicated activation wavelength illustrated in Appendix IX scenario C), it is possible that the OLT CT issues an Assign_ONU-ID message to the ONU's known serial number. In this case, the ONU could transition through the Serial Number state (O2-3) into the Ranging state (O4) without ever having responded to an in-band serial number grant.

The ranging grants are addressed to the default Alloc-ID of an ONU in the Ranging state (O4), carry a burst profile that has been previously communicated to the ONU, and have the PLOAMu flag set. The ranging grants should have the DBRu flag reset, carry the GrantSize of 0, and be accompanied by the appropriate quiet window. In some cases, for example, after a loss of power or a protection switching event, the OLT CT may assign ONU-IDs and issue ranging grants to the known ONUs without explicitly rediscovering their serial numbers.

In deciding on the size of the quiet window to accompany a ranging grant, the OLT CT may use the ranging information obtained from the serial number response, during the previous activations of the ONU or, in case of a protected ODN, over an alternative ODN path.

If the OLT CT has previously measured the ONU's round-trip delay during the serial number acquisition phase, or during earlier activations of the ONU, or from another channel (e.g., dedicated activation wavelength channel illustrated in Appendix IX scenario C), it is possible that the OLT CT issues a Ranging_Time message with the previously calculated equalization delay. In this case, the ONU could transition through the Ranging state (O4) into the Operation state (O5) without having responded to a ranging grant.

When the ONU is in the Operation state (O5), the OLT CT may use any grant to that ONU to perform in-service round-trip delay measurement and equalization delay adjustment.

The OLT CT at its discretion may deactivate a previously assigned ONU-ID, forcing the ONU to discard its ComTC layer configuration information (see Tables 12-4 and 12-5) and re-enter the activation, or disable a specific serial number forcing that ONU into the Emergency Stop state (O7) and inhibiting any upstream transmissions or state transitions by that ONU until an explicit permission in the future.

The OLT CT may use equalization delay readjustment, ONU-ID deactivation, and serial number disabling for the purposes of rogue ONU prevention, detection, and isolation. In an extreme situation when rogue behaviour is exhibited by an ONU that has not been able to declare its serial number, the OLT CT may globally disable all the ONUs in its downstream wavelength channel and subsequently re-enable the conformant ONUs one by one.

12.6 TWDM ONU power levelling

In TWDM, power levelling is a mechanism that allows an ONU to change its transmit optical power by optimizing the ONU attenuation levels in order to improve the signal-to-noise ratio (SNR) at the OLT CT. There are two methods for the invocation of the power levelling mechanism: ONU-activated and OLT-activated.

Power levelling support is optional for an ONU. If the ONU does support power levelling, it shall at least be capable of supporting 3 dB and 6 dB attenuation levels, and shall be able to announce its power levelling capabilities (within the Serial_Number_ONU and Tuning_Response PLOAM messages) and to support the OLT-activated power levelling protocol (the Change_Power_Level PLOAM messages and the respective responses within the Acknowledgement PLOAM message). The ONU that supports power levelling is expected to follow the OLT guidance (within the Channel_Profile PLOAM message) while executing ONU-activated power levelling.

Power levelling support is optional for an OLT. If the OLT supports power levelling, it shall provide guidance for ONU-activated power levelling (within Channel_Profile PLOAM message) and shall support the OLT-activated power levelling protocol (the Change_Power_Level PLOAM messages and the respective responses within the Acknowledgement PLOAM message). The criteria and specific mechanisms for selecting the target attenuation levels are left to the implementation.

12.6.1 ONU-activated power levelling

In TWDM, an ONU may apply power levelling autonomously upon activation in the Serial Number state (O2-3) or upon wavelength channel handover in the Upstream Tuning state (O9). The OLT CT may guide the ONU-activated power levelling by announcing the default ONU attenuation level and the Response Threshold within the Channel_Profile PLOAM message.

When an ONU begins transmission in states O2-3 or O9, it sets the smallest supported attenuation level which is greater than or equal to the default attenuation level specified by the OLT CT, and then gradually decreases its attenuation level until it receives a response from OLT CT. If establishing communication with the OLT CT in states O2-3 or O9 involves changing the upstream Tx wavelength, the ONU should exhaust the applicable Tx wavelength options before decreasing its attenuation level. However, the ONU should return to the full unattenuated launch optical power once the total number of PLOAM messages (Serial_Number_ONU in state O2-3, Tuning_Response in state O9) it has sent reaches the specified Response Threshold.

Once the ONU reaches zero attenuation level while in states O2-3 or O9, it makes no further adjustment to its launch optical power.

12.6.2 OLT-activated power levelling

In TWDM, OLT-activated power levelling occurs in the Operation state (O5).

To adjust the launch optical power of a specific ONU or all tuned-in ONUs, the OLT CT may send a directed or broadcast Change_Power_Level PLOAM message. The launch optical power adjustment can be either direct (specifying a certain attenuation level) or incremental (specifying the direction of launch optical power change).

If an ONU receives a Change_Power_Level PLOAM message with invalid launch optical power adjustment instruction, the ONU responds with an Acknowledgement PLOAM message containing the completion code that indicates a Parameter Error and reporting its current attenuation level. The launch optical power adjustment instruction is invalid, if the ONU does not support the directly specified attenuation level, or if the ONU is unable to incrementally increase or decrease launch optical power, because it has already reached, respectively, its lowest or highest supported attenuation level.

If an ONU receives a Change_Power_Level PLOAM message with a valid launch optical power adjustment instruction ONU, it optionally responds with an Acknowledgement PLOAM message containing Busy completion code and reporting its old (starting) attenuation level. The ONU then commences the launch optical power adjustment operation. Once the launch optical power adjustment operation is completed, the ONU sends another Acknowledgement PLOAM message (referring the sequence number of the original Change_Power_Level PLOAM message) containing OK completion code and reporting its new attenuation level.

The OLT CT should abstain from issuing repeated Change_Power_Level PLOAM messages to the ONU without receiving an Acknowledgement of the previous launch optical power adjustment operation.

The OLT CT may use the Change_Power_Level PLOAM message to request a report of ONU's current launch optical power. Upon receiving such a request, an ONU responds with an Acknowledgement PLOAM message containing OK completion code and reporting its current attenuation level.

13 OLT and ONU timing relationships

13.1 ONU transmission timing and equalization delay

The material presented in this clause is based on the following definitions:

1) The start of the downstream PHY frame is the moment of transmission/reception of the first bit of the PSync field.
2) The reference start time of an upstream PHY burst is the moment of transmission/reception of the first bit of the word or block identified by the StartTime of the corresponding bandwidth allocation structure. This is the first bit of the FS burst header.

3) The start of the upstream PHY frame is the moment of transmission/reception (either actual or calculated) of the first bit of the word or block that, if present, would be identified by the StartTime pointer of zero value.

4) The quiet window offset at the OLT CT is the elapsed time between the start of the downstream PHY frame in which the serial number grant or ranging grant is transmitted and the earliest possible start of an upstream PHY burst carrying the response PLOAM.

5) The upstream PHY frame offset at the OLT CT, Teqd, is the elapsed time between the start of the downstream PHY frame carrying a specific BWmap and the upstream PHY frame implementing that BWmap[5].

An ODN can be characterized by two parameters: the minimum fibre distance, L_{min} and the maximum differential fibre distance, D_{max}. These parameters are expressed in kilometres, are fixed by ODN design and are known to the OLT CT *a priori*. The fibre distance L_i, of ONU_i satisfies:

$$L_{\min} \le L_i \le L_{\min} + D_{\max} \tag{13-1}$$

13.1.1 Timing of ONU upstream transmissions

All ONU transmission events are referenced to the start of the downstream PHY frame carrying the BWmap that contains the corresponding burst allocation series. Note, in particular, that an ONU transmission event is not referenced to the receipt of the corresponding burst allocation series itself, which may occur at a variable time into the downstream PHY frame.

At all times, the ONU maintains a running upstream PHY frame clock that is synchronized to the downstream PHY frame clock and offset by a precise amount. The amount of offset is the sum of two values: the ONU response time and the requisite delay, as shown in Figure 13-1.

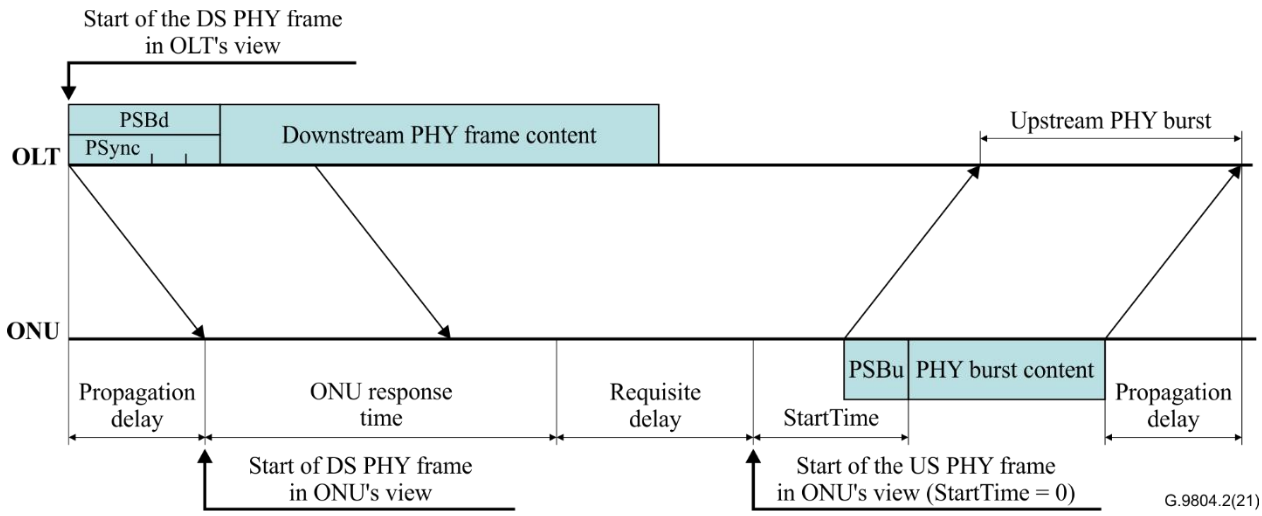


Figure 13-1 – ONU timing diagram: General case

The range of ONU response time is a system-wide parameter that is chosen to give the ONU sufficient time to receive the downstream frame, including the upstream bandwidth map, perform downstream and upstream FEC as needed, and prepare an upstream response. All ONUs are required to have an ONU response time of 35 ± 1 μs; that is, $RspTime_{\min}$= 34 μs, $RspTime_{\max}$ = 36 μs. Further, each ONU_i is required to know its response time, $RspTime_i$.

[5] In [b-ITU-T G.984.3], this parameter is referred to as a zero-distance equalization delay.

The general term "requisite delay" refers to the total extra delay that an ONU may be required to apply to the upstream transmission beyond its regular response time. The purpose of the requisite delay is to compensate for variation of propagation and processing delays of individual ONUs, and to avoid or reduce the probability of collisions between upstream transmissions. The value of requisite delay changes with the state of the ONU as described below.

13.1.2 Timing relationships and quiet window during serial number acquisition

The following discussion is illustrated in Figure 13-2.

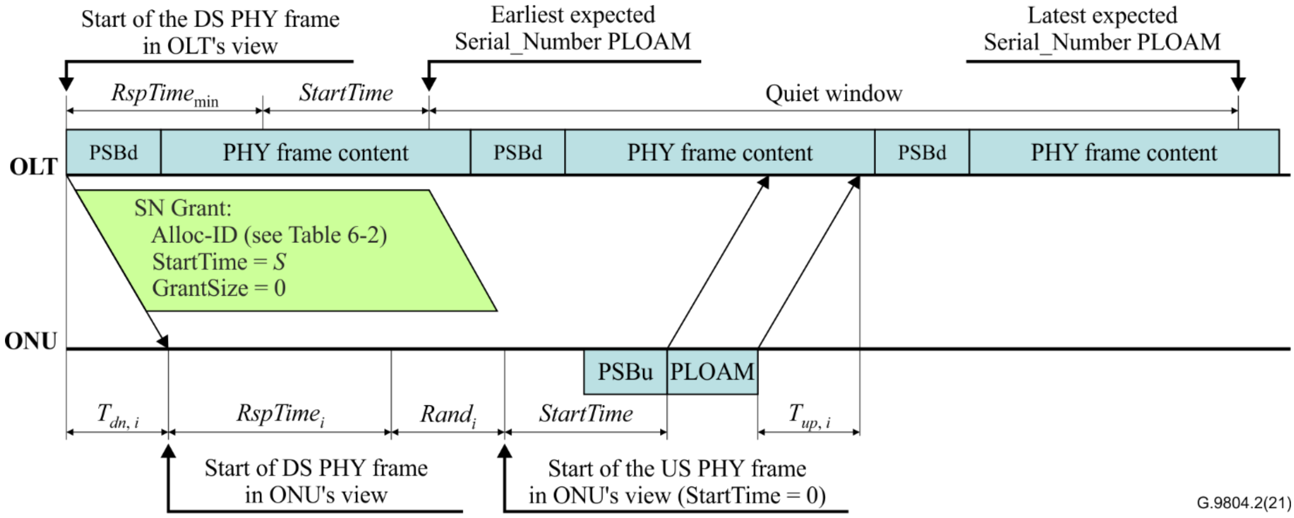


Figure 13-2 – Timing relationships during serial number acquisition

While an ONU is in the Serial Number state (O2-3), it stays synchronized to the downstream wavelength channel. When an ONU in this state receives a serial number grant, it transmits a serial number response in the form of a Serial_Number_ONU PLOAM message.

To avoid collisions between a serial number response from an ONU in the Serial Number state (O2-3) and the regular upstream bursts from the ONUs in the Operation state (O5), the OLT CT opens a quiet window to temporarily suppress upstream transmission by the in-service ONUs.

Since the serial number grant is a broadcast bandwidth allocation addressed to all ONUs in the Serial Number state (O2-3), more than a single ONU may respond to it, and a collision may occur when more than one serial number response arrives at the OLT CT at the same time. To reduce the probability of collision, the requisite delay in the Serial Number state (O2-3) is a locally-generated random delay, $Rand_i$. The random delay is uniformly distributed between zero and the maximum random delay, which is a parameter of the ONU activation collision-based function (see clause 7.5.2.1), and is expressed in time quanta. For each response to a serial number grant, the ONU generates a new random delay.

The offset of the quiet window during serial number acquisition is determined by the minimum delays in the system, including the minimum round-trip propagation delay and minimum ONU processing time, as well as the dynamically generated StartTime value of the serial number grant:

$$W_0^{SN} = RspTime_{\min} + \frac{L_{\min}\left(n_{\mathrm{dn}} + n_{\mathrm{up}}\right)}{c} + StartTime \cdot Q_0 \tag{13-2}$$

Here c is the speed of light in km/μs, $RspTime_{\min}$ is the minimum response time of an ONU, n_{dn} and n_{up} are group velocity refractive indices of the fibre at the downstream and upstream wavelengths, respectively, and Q_0 is the time quantum.

The size of the quiet window during serial number acquisition is determined by the maximum variation of the unknown round-trip delay components and the duration of the serial number response burst. The unknown round-trip delay components include round-trip propagation delay, ONU response time, and ONU random delay. The serial number response burst includes preamble, delimiter, upstream FS header with a Serial_Number_ONU PLOAM message, and FS trailer.

$$W_{\Delta}^{SN} = RspTime_{\text{var}} + \frac{D_{\max}\left(n_{\text{dn}} + n_{up}\right)}{c} + Rand_{\max} + T_{SN} \tag{13-3}$$

Here $RspTime_{\text{var}}$ is the variation of the ONU response time, and $Rand_{\max}$ is maximum random delay. The duration of the serial number response burst, T_{SN}, which is, typically, less than 0.3 µs, is negligible compared with the other components.

For an ODN with a differential fibre distance of 20 km, the values are:

– 200 µs for the variation of round-trip propagation delay;

– 2 µs for the variation of ONU response time;

– 48 µs for the ONU's maximum random delay.

The suggested duration of the quiet window during serial number acquisition is 250 µs.

For an ODN with a differential fibre distance of 40 km, the values are:

– 400 µs for the variation of round-trip propagation delay;

– 2 µs for the variation of ONU response time;

– 48 µs for the ONU's maximum random delay.

The suggested duration of the quiet window during serial number acquisition is 450 µs.

13.1.3 Timing relationships and quiet window during ranging

The following discussion is illustrated in Figure 13-3.

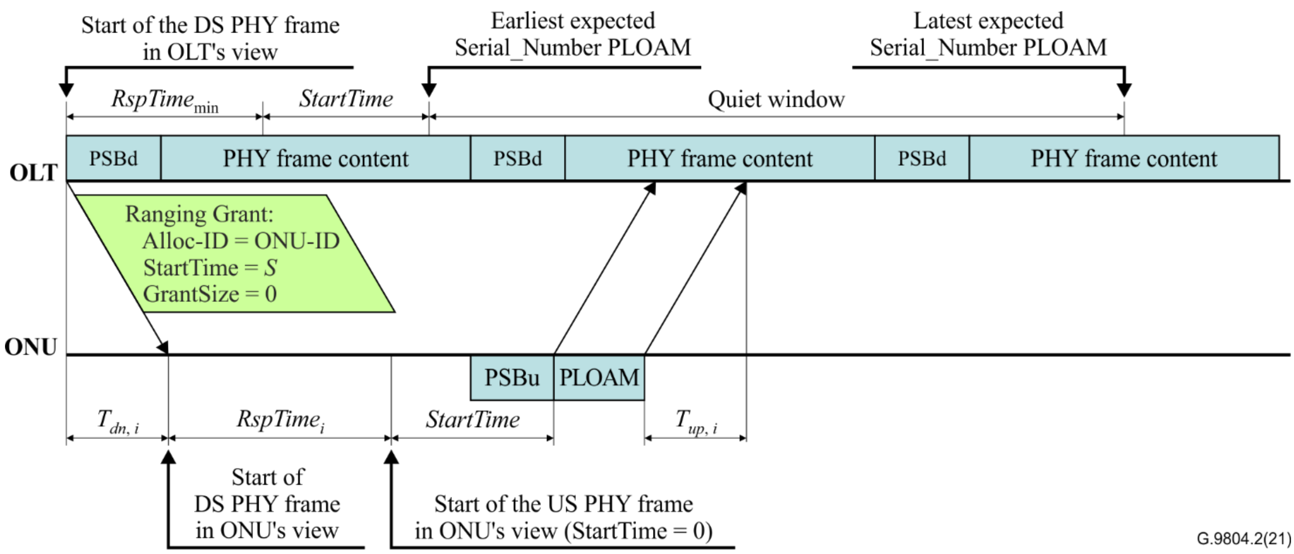


Figure 13-3 – Timing relationships during ranging

An ONU enters the Ranging state (O4) upon assignment of ONU-ID. While in the Ranging state (O4), the ONU interprets any directed bandwidth allocation with the PLOAMu flag set as a ranging grant and responds to it with a Registration PLOAM message.

To avoid collisions between the ranging grant response and the regular upstream bursts from the ONUs in the Operation state (O5), the OLT CT opens a quiet window to temporarily suppress upstream transmission by the in-service ONUs. During ranging, the requisite delay is equal to zero.

The offset of the quiet window during ranging is determined by the minimum round-trip propagation delay and minimum ONU processing time, as well as the dynamically generated StartTime value of the ranging grant:

$$W_0^{RNG} = RspTime_{\min} + \frac{L_{\min}\left(n_{\mathrm{dn}} + n_{up}\right)}{c} + StartTime \cdot Q_0 \tag{13-4}$$

The size of the quiet window during ranging is determined by the maximum variation of the unknown round-trip delay components and the duration of the registration burst. If the OLT CT has not already obtained a measure or estimate of the round-trip delay during serial number acquisition, the unknown round-trip delay components include round-trip propagation delay and ONU response time. The ranging response burst includes preamble, delimiter, upstream FS header with a Registration PLOAM message, and FS trailer.

$$W_\Delta^{RNG} = RspTime_{\mathrm{var}} + \frac{D_{\max}\left(n_{dn} + n_{up}\right)}{c} + T_{RG} \tag{13-5}$$

The duration of the ranging response burst T_{RG}, which is, typically, less than 0.3 μs, is negligible compared with the other components.

For an ODN with a differential fibre distance of 20 km, the values are:

– 200 μs for the variation of round-trip propagation delay;

– 2 μs for the variation of ONU response time.

The maximum suggested duration of the quiet window during ranging is 202 μs.

For an ODN with a differential fibre distance of 40 km, the values are:

– 400 μs for the variation of the round-trip propagation delay;

– 2 μs for the variation of the ONU response time.

The maximum suggested duration of the quiet window during ranging is 402 μs.

In practice, the maximum suggested values derived above may be reduced if the OLT CT makes use of the ranging information obtained from the serial number response, during the previous activations of the ONU or, in case of a protected ODN, over an alternative ODN path.

13.1.4 Calculating the equalization delay

The OLT CT selects T_{eqd}, the upstream PHY frame offset, based on the ODN design parameters:

$$T_{eqd} \geq RspTime_{\max} + \left(L_{\min} + D_{\max}\right)\frac{\left(n_{\mathrm{dn}} + n_{up}\right)}{c} \tag{13-6}$$

The selected value of T_{eqd} can be further adjusted to ensure equalization delay consistency across TWDM channels, as described in Appendix VII, and remains constant thereafter.

When the OLT CT issues a ranging grant to an ONU in the Ranging state (O4), the OLT CT accurately measures the elapsed time Δ_i^{RNG} between the downstream PHY frame containing the ranging grant and the upstream PHY burst containing the response Registration PLOAM (see Figure 13-4). Given the selected upstream PHY frame offset, the equalization delay of the ONU is found as:

$$EqD_i = T_{eqd} - RTD_i = T_{eqd} - \left(\Delta_i^{RNG} - StartTime \cdot Q_0\right) \tag{13-7}$$

Alternatively, the OLT CT can measure the equalization delay directly by timing the duration between the actual and desired arrival times of the burst containing the Registration PLOAM message.

The value of equalization delay calculated by the OLT CT and communicated to the ONU is accurate to $Q_0/32$ or 1/3,110,400,000 seconds. The ONU is required to maintain the granularity of the equalization delay adjustment of not more than eight integer bit periods.

Once the ONU is supplied with its equalization delay value, it is considered synchronized to the beginning of the upstream PHY frame. The upstream data is transmitted within the interval specified by the allocation structure with respect to the beginning of the upstream PHY frame.

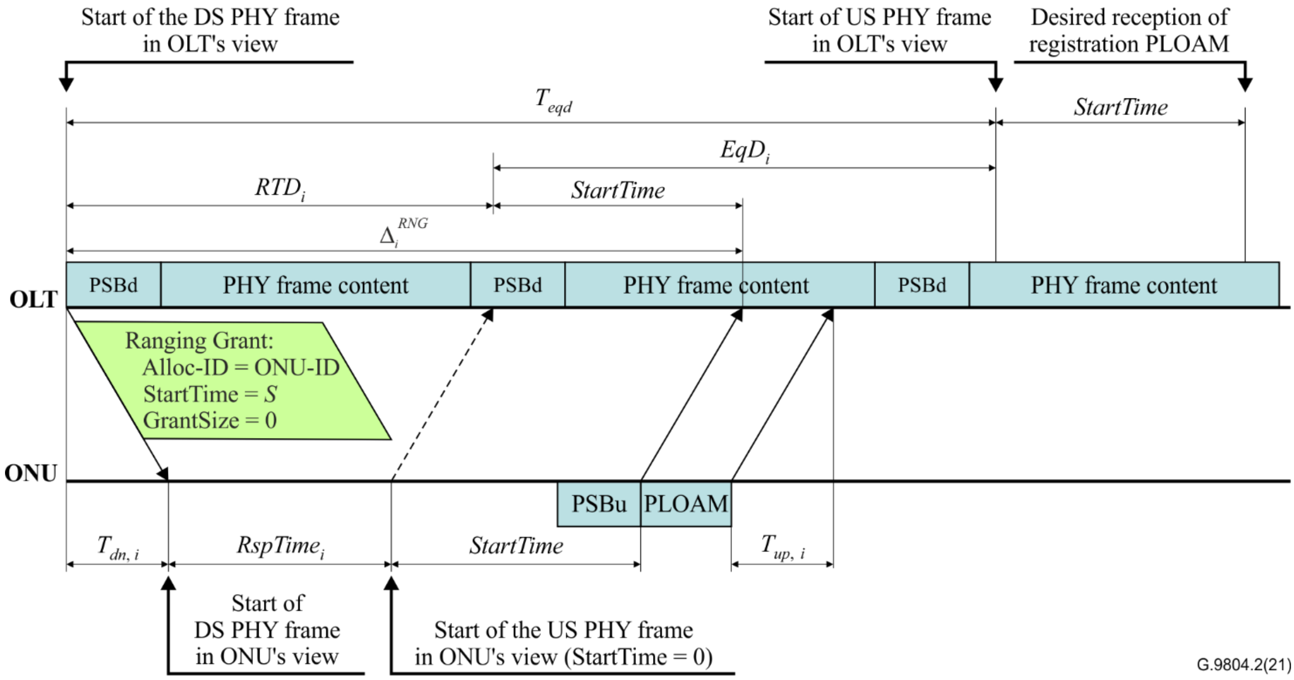


Figure 13-4 – Equalization delay calculation during ranging

13.1.5 Timing relationships during operation

In the Operation state (O5), the ONU maintains its upstream PHY frame clock synchronized with the downstream PHY frame clock and offset by the sum of the ONU response time and the assigned equalization delay specified by the OLT CT in the Ranging_Time message, as shown in Figure 13-5. When the ONU receives a bandwidth allocation, it transmits data starting at the upstream word indicated in the StartTime field. During operation, the requisite delay is equal to the assigned equalization delay.

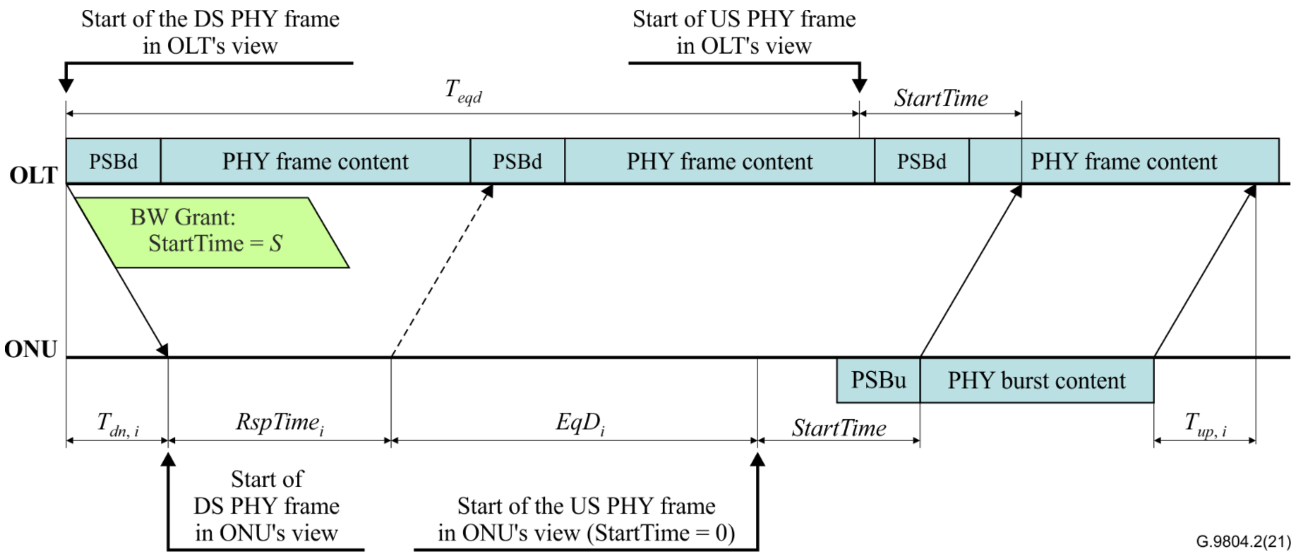


Figure 13-5 – Timing relationships in the Operation state (O5)

13.1.6 In-service equalization delay adjustment

The OLT CT expects the ONU's upstream transmission to arrive at a fixed time during the upstream PHY frame. The arrival phase of the ONU transmission may drift due to aging, temperature changes and other factors. In those cases, the equalization delay can be recalculated and adjusted from the drift of the upstream transmission. In-service equalization delay adjustment allows small corrections to be made without having to re-range the ONU.

The change in the equalization delay is equal to the drift time with the opposite sign. If the PHY burst arrives early, the OLT CT increases the equalization delay by the drift time. If the PHY burst arrives late, the OLT CT reduces the equalization delay by the drift time. Equalization delay adjustments are communicated to an ONU in the Operation state (O5) using the Ranging_Time PLOAM message. A relative delay parameter can be conveniently used for this purpose.

To avoid excessively frequent equalization delay adjustments and to ensure ONU compliance, the OLT CT maintains two drift thresholds applicable to all ONUs. The lower threshold establishes the safe bounds within which the transmission drift is considered acceptable and does not require any mitigating action. When the drift exceeds the lower threshold, the OLT CT calculates a new equalization delay value and transmits it to the ONU using the Ranging_Time PLOAM message. The OLT CT also recognizes a drift of window (DOWi) event. The upper threshold establishes the critical bounds beyond which the transmission drift can affect the other ONUs on the PON. If the drift exceeds the upper threshold (an event which should not happen as long as the ONU complies with the equalization delay adjustments), the OLT CT declares transmission interference warning (TIWi) and takes further mitigating actions that may include deactivation or disabling of the offending ONU-ID, or execution of a rogue ONU diagnostic procedure.

The suggested threshold values of DOW_i and TIW_i are invariant in terms of time quantum are expressed as pointed out in Table 13-1.

Table 13-1 – Suggested thresholds for DOW_i and TIW_i

	In time quantum
DOW_i	$\pm Q_0/4$
TIW_i	$\pm Q_0/2$

13.1.7 Quiet window implementation considerations

When in the Serial Number and Ranging states, the ONUs transmit Serial_Number_ONU PLOAM messages and Registration PLOAM messages. Because the OLT CT does not yet know the equalization delay for these ONUs, it opens a quiet window to prevent collision between the serial number or ranging responses and the regular upstream transmissions by in-service ONUs.

Consider the example shown in Figure 13-6. Here $L_{min} = 0$; $D_{max} = 20$ km; $T_{eqd} = 236$ µs. This example focuses on serial number acquisition and assumes that the propagation delay is bounded by 100 µs while the ONU response time for different ONUs may vary, unbeknown to the OLT CT, within the 35 ± 1 µs range. Therefore, if the OLT CT transmits a downstream PHY frame with a specific BWmap at time t_0, coinciding with the start of downstream PHY frame *N*, the earliest it can schedule the upstream PHY frame implementing this BWmap is 236 µs later. The OLT CT's objective is to create a 250 µs-long quiet window starting at time $t_Z = t_0 + 236$ µs.

The BWmap supplied with downstream PHY frame *N* is empty, while the sole allocation structure of the BWmap transmitted with downstream PHY frame *N* + 1 is a serial number grant with StartTime offset of 77 µs. The start of the possible serial number response transmission window is offset by at least 111 µs with respect to the start of the frame carrying the serial number grant, and by at least 236 µs, with respect to frame *N*.

Note that PHY frame *N*–1 has to provide the necessary burst mode margin at the end of the BWmap.

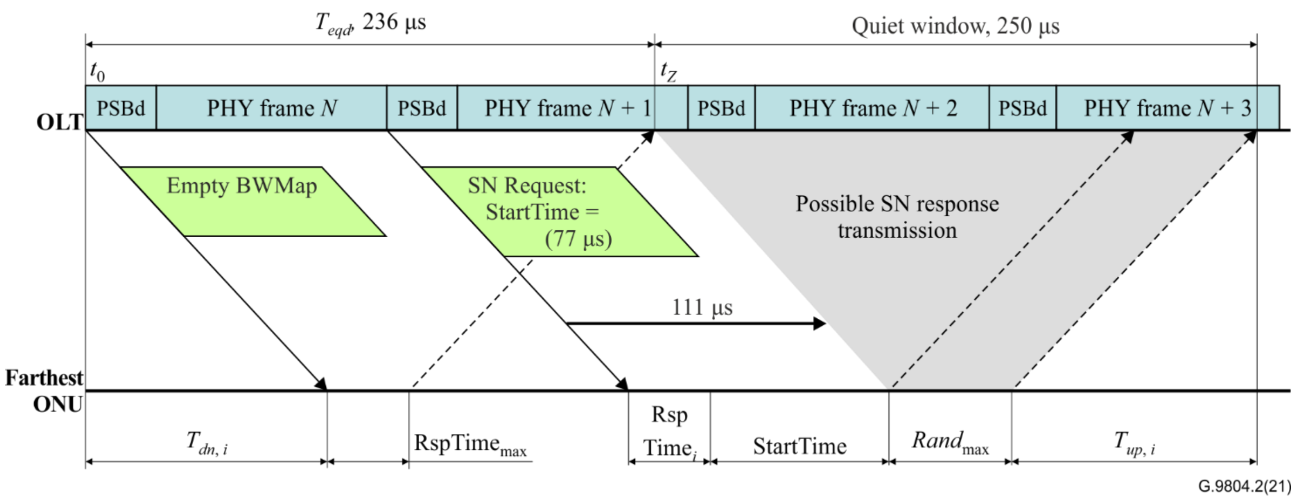


Figure 13-6 – Quiet window creation

Since each such quiet window affects at least two and possibly three consecutive bandwidth maps, the OLT CT must ensure that the impact of the quiet windows on the bandwidth and jitter-sensitive traffic flows is minimized. This may be achieved, for example, by re-arranging the BWmaps and providing extra allocations to the affected Alloc-IDs immediately before and/or immediately after the quiet window.

If some information about ONU locations is available to the OLT CT, it may be able to create a smaller, better targeted and less intrusive quiet window, whose offset with respect to the start of the downstream PHY frame depends on the fibre distance of the closest ONU, and whose size depends on the maximum differential fibre distance.

13.1.8 Fibre distance measurement

The OLT CT can estimate the fibre distance based on the round-trip measurement using $RspTime_i$, the actual response time of ONU_i, which can be obtained via the OMCC. The estimate of the fibre distance between the OLT CT and the given ONU_i (in metres) may be obtained according to the following formula:

$$FD_i = \left(RTT_i - RspTime_i - EqD_i - StartTime \cdot Q_0\right) \times 102 \qquad (13\text{-}8)$$

Here RTT_i is the round-trip time, i.e., the actual offset of the start of the upstream PHY burst with respect to the start of the downstream PHY frame specifying that burst, in microseconds, as measured by the OLT CT; $RspTime_i$ is the true ONU response time in microseconds, as reported by ONU_i; EqD_i is the equalization delay of the ONU; *StartTime* is the dynamically generated StartTime value of the burst when the measurement is conducted; Q_0 is the time quantum; and the numeric coefficient of 102 m/μs is a best fit value reflecting the range of refractive indices that [b-ITU-T G.652] fibres exhibit in the field. This method is capable of producing an estimate that is approximately ±1% accurate.

13.2 Time of day distribution

This clause describes the ComTC layer method that is used to obtain the accurate time of day (ToD) at an ONU, the timing relations between OLT CT and ONU, and the timing error analysis.

The principle of operation is as follows. It is assumed that the OLT CT has an accurate real time clock, obtained through means beyond the scope of this Recommendation. The OLT CT informs the ONU of the time of day when a certain downstream PHY frame would arrive at a hypothetical ONU that had zero equalization delay and zero ONU response time. The certain downstream PHY frame is identified by *N*, the value of its superframe counter, which is an existing feature of the protocol. The information transfer is accomplished using OMCI, and does not need to be in real time. Having learned the ToD arrival time of PHY frame *N*, the ONU can use its equalization delay and response time to compute the ToD associated with the arrival of an arbitrary downstream PHY frame with very high accuracy.

13.2.1 Notation

$\boldsymbol{T}\mathbf{stamp}_N$ – This term refers to the exact ToD at which the first bit of downstream PHY frame *N* arrives at a hypothetical ONU that has an EqD of zero and a response time of zero. The arrival of the signal at the ONU is defined to be the instant at which the optical signal crosses the optical connector or splice that is the boundary between the ODN and the ONU.

$\boldsymbol{T}\mathbf{send}_N$ – The exact ToD at which the first bit of downstream PHY frame *N* departs from the OLT CT. The departure of the signal is defined to be the instant at which the optical signal crosses the optical connector or splice that is the boundary between the OLT CT and the ODN.

$\boldsymbol{T}\mathbf{recv}_{N,i}$ – The exact ToD at which the first bit of downstream frame PHY *N* arrives at ONU_i. The arrival of the signal at the ONU is defined to be the instant at which the optical signal crosses the optical connector or splice that is the boundary between the ODN and the ONU.

$\boldsymbol{RspTime}_i$ – The value of the response time for ONU_i, which lies in the range of 34 to 36 microseconds.

$\boldsymbol{T}_{\mathbf{eqd}}$ – The offset of the upstream PHY frame with respect to the downstream PHY frame at the OLT CT location. The OLT CT adjusts the equalization delay of each ONU such that, for all ONUs, the start of the upstream frame at the OLT CT occurs T_{eqd} seconds after the start of the downstream frame.

– $\boldsymbol{n}_{up}$ – The group velocity refractive index for the specific upstream wavelength.

– $\boldsymbol{n}_{dn}$ – The group velocity refractive index for the specific downstream wavelength.

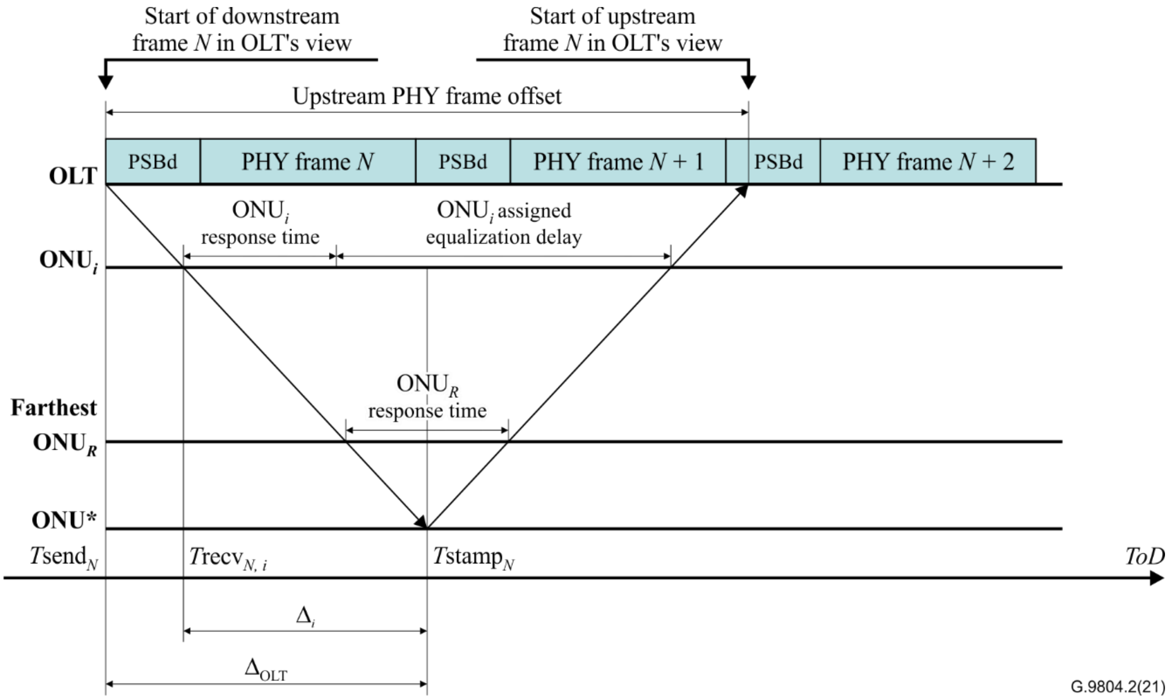


Figure 13-7 – Time of day calculations

13.2.2 ONU clock synchronization process

The following process synchronizes the slave clock of the ONU to the master clock of the OLT CT:

1) The OLT CT selects a downstream PHY frame to be used as the timing reference. This PHY frame is identified by superframe counter N and has an associated $T\text{send}_N$ value. It is recommended that the selected PHY frame be within a ten-second window of the current time.

2) The OLT CT calculates the $T\text{stamp}_N$ value, which is based on the $T\text{send}_N$ value of PHY frame N. This calculation is given by:

$$Tstamp_N = Tsend_N + \Delta_{OLT} \tag{13-9}$$

where:

$$\Delta_{OLT} = Teqd \frac{n_{\mathrm{dn}}}{n_{up} + n_{dn}} \tag{13-10}$$

Note that the $T\text{send}_N$ and $T\text{stamp}_N$ values are all referenced to the optical interface to ensure that they are invariant to the implementation. The OLT CT is responsible for compensating for all its internal delays.

3) This value pair (N, $T\text{stamp}_N$) is stored locally at the OLT CT side.

4) The OLT CT sends this value pair (N, $T\text{stamp}_N$) to one or more ONUs using OMCI.

5) ONU$_i$ calculates the $T\text{recv}_{N,i}$ value based on the $T\text{stamp}_N$ and its own timing parameters. This calculation is given by:

$$Trecv_{N,i} = Tstamp_N - \Delta_i \tag{13-11}$$

where:

$$\Delta_i = \left(EqD_i + RspTime_i\right)\frac{n_{dn}}{n_{up} + n_{dn}} \tag{13-12}$$

The exact value of response time for ONU_i must be used. Note that the $T\mathrm{stamp}_N$ and $T\mathrm{recv}_N$ values are all referenced to the ONU's optical interface to ensure that they are invariant to the implementation. The ONU is responsible for compensating for all of its internal delays.

6) When ONU_i receives an arbitrary downstream frame K, it can set its ToD clock to the value $T\mathrm{recv}_{K,i} = T\mathrm{recv}_{N,i} + (K - N) \times 125.0$ µs. Care should be taken to account for the superframe counter rolling over. The ONU is expected to complete clock synchronization within 10 s of communication of the (N, $T\mathrm{stamp}_N$) value pair using OMCI.

7) Whenever the ONU's equalization delay is adjusted while the setting of the ToD clock is still pending, the ONU makes the commensurate adjustment in its predicted $T\mathrm{recv}_{N,i}$ value. In this way, the ToD clock tracks any drifts in propagation delay of the PON system.

It is assumed (and holds true for a common HSP system) that the OLT CT supports one and only one ToD clock domain. If this is the case, then the system clock can be synchronized to the ToD clock, thus allowing the periodicity of the ToD distribution procedure to be relaxed. The case of multiple ToD clock domains per OLT CT is out of scope of this Recommendation.

13.2.3 Performance analysis

This clause does not impose any new system requirements. The analysis contained herein is based on the requirements formulated elsewhere in this Recommendation.

13.2.3.1 Equalization delay accuracy

The accuracy of equalization delay is determined by the DOW threshold (see clause 13.1.6), which is $\pm Q_0/4$. This is very much smaller than the overall system timing requirement of 1 µs, so this can likely be neglected.

13.2.3.2 Fibre propagation delay

For typical [b-ITU-T G.652] fibres, the maximum estimate of the index correction factor is thus:

$$\frac{n_{dn}}{n_{dn}+n_{up}} = I_{cf}$$

Using the I_{cf} would result in a maximum systematic error of a certain value, caused by corresponding upstream and downstream wavelength in PON system. With this value, the propagation error of a typical length PON system can be calculated afterwards. It should be noted that different fibres may exhibit different absolute refractive indices; however, the relative dispersion between upstream wavelength and downstream wavelength is very well controlled. See Appendix II for the details of the error analysis.

13.2.3.3 Internal timing corrections

Both the OLT CT and ONU are responsible for compensating for their internal delays from wherever the logical computations and/or event triggers occur to the optical interfaces, which are used as reference points for standardization purposes. In the PON system, the TDMA requirements imply that these internal delays are stable at least over each ranging life-cycle to the accuracy given above ($\pm Q_0/4$). The stability and predictability of PON equipment over longer time periods is not specified. However, one can expect the cycle-to-cycle variability to be contained within the bounds of $\pm Q_0/2$, which corresponds to two uncontrolled serializer-deserializer delays in the downstream link. Even in this case, the resulting timing uncertainty of $\pm Q_0/2$ is very small.

14 Performance monitoring, supervision, and defects

This clause focuses on mechanisms to detect link failure and monitor the health and performance of the links. It does not cover functions that may utilize the performance monitoring information, such as station management, bandwidth allocation or provisioning.

14.1 Performance monitoring

To facilitate troubleshooting, it is desirable that OLT channel termination and ONU maintain a variety of performance monitoring (PM) counters. The collected counter values may trigger actions ranging from threshold crossing alerts to alarms to protection switching, which are largely beyond the scope of this Recommendation.

This clause identifies mandatory and optional PM parameters, and for the PM parameters collected at the OLT CT, it indicates whether they should be collected individually for each ONU or on an aggregate basis for all ONUs.

Monitoring of optical parameters, for example, transmitted and received optical power, is specified in [ITU-T G.988].

Counters collected at the ONU are available to the OLT CT using OMCI.

Table 14-1 summarizes performance monitoring counters, while Table 14-2 lists other performance monitoring parameters.

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by:			Notes
			Each ONU for each wavelength channel	OLT CT for each ONU_i	OLT CT	
PHY PM						
Corrected FEC bits	M	The number of bits that were corrected by the FEC function.	Yes, for all traffic flows.	Yes, if upstream FEC is enabled for ONU_i	N/A	
Corrected FEC codewords	M	Count of FEC codewords that contained errors but were corrected by the FEC function.	Yes, for all traffic flows.	Yes, if upstream FEC is enabled for ONU_i.	N/A	
Uncorrectable FEC codewords	M	Count of FEC codewords that contained errors and could not be corrected by the FEC function.	Yes, for all traffic flows.	Yes, if upstream FEC is enabled for ONU_i.	Yes	
Total FEC codewords	M	Count of total received FEC codewords.	Yes, for all traffic flows.	Yes, if upstream FEC is enabled for ONU_i.	Yes	
Total received words protected by BIP-32	M	Count of received 4-byte words that are included in BIP-32 check.	N/A	Yes	Yes	
BIP-32 error count	M	Count of bit errors according to BIP-32 (Note 1).	N/A	Yes	Yes	
PSBd HEC error count	O	HEC error in any of the fields of PSBd.	Yes, for all traffic flows.	N/A	N/A	

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	Collected by: OLT CT for each ONU$_i$	Collected by: OLT CT	Notes
FS HEC error count	O	DS FS header HEC errors received.	Yes, for all traffic flows.	Yes	N/A	
Unknown profile count	O	ONU could not transmit because the specified burst profile was not known.	Yes	N/A	N/A	
LODS PM						
Total number of LODS events	M	Counter of state transitions from O5.1/O5.2 to O6	Yes	N/A	N/A	ONU local event
LODS events restored in the operating TWDM channel	M	LODS cleared without retuning	Yes	N/A	N/A	ONU local event
LODS events restored in the pre-configured protection TWDM channel	M	WLCP On. ONU retunes to the pre-configured channel.	Yes	N/A	N/A	ONU local event
LODS events restored in a discretionary TWDM channel	M	WLCP off. ONU retunes to the channel of its choice.	Yes	N/A	N/A	ONU local event
LODS events resulting in ONU reactivation without synchronization being reacquired	M	Either TO2 (without WLCP) or TO3+TO4 (with WLCP) expire before the downstream channel is reacquired.	Yes	N/A	N/A	ONU local event
LODS events resulting in ONU reactivation after upstream handshake failure in pre-configured TWDM channel.	M	Timer TO5 expiration in pre-configured TWDM channel	Yes	N/A	N/A	ONU local event
LODS events resulting in ONU reactivation after upstream handshake failure in discretionary TWDM channel.	M	Timer TO5 expiration in discretionary TWDM channel to which ONU retunes as a channel of its choice.	Yes	N/A	N/A	ONU local event
XGEM PM						
Transmitted XGEM frames	M	Total number of XGEM frames transmitted.	Yes	No	Yes	
Transmitted XGEM frames per XGEM port	O	The number of XGEM frames transmitted.	Yes, per XGEM port.	No	Yes, per XGEM port.	
Received XGEM frames	M	Total number of XGEM frames received.	No	No	Yes	

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU_i	OLT CT	Notes
Received XGEM frames per XGEM port	O	The number of XGEM frames received.	Yes, per XGEM port that belongs to the ONU.	No	Yes, per XGEM port.	
Count of the number of transmitted XGEM frames with LF bit NOT set	O	Number of transmit fragmentation operations.	Yes	No	Yes	
Count of XGEM frame header HEC errors	M	Number of events involving loss of XGEM channel delineation.	Yes	Yes	No	
Count of FS frame words lost due to XGEM frame HEC error.	O	Aggregate severity measure of the loss of XGEM channel delineation events. Note that the number of lost XGEM frames is not available.	Yes	Yes	N/A	
XGEM key error count	M	XGEM frames discarded because of unknown or invalid encryption key. Examples include: no unicast or broadcast key established for specified key index, key index indicating encrypted XGEM frame on an XGEM port that is not provisioned for encryption, key index indicating upstream encryption on an XGEM port that is provisioned for downstream encryption only, or invalid key index (11). This count is included in the Rx XGEM frame count.	Yes	Yes	N/A	
UTILIZATION PM						
Transmitted bytes in non-idle XGEM frames	M	Measure of downstream utilization	Yes	Yes	Yes	
Received bytes in non-idle XGEM frames	M	Measure of upstream utilization	Yes	Yes	Yes	

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	Notes
Count of DBA inability to assign guaranteed bandwidth in the presence of demand	O	Indication of upstream congestion	N/A	Yes	Yes	
PLOAM PM						
SN grant count	O	Serial number grants for ONU discovery.	N/A	N/A	Yes	
PLOAM MIC errors	O	Counter of received PLOAM messages with MIC errors	Yes	Yes	N/A	
PLOAM timeouts	O	Retransmission count: missing, late or errored response. No response to key request or Request_Registration, lack of ACK, etc.	N/A	N/A	Yes	
DG count	O	Count of dying gasp bursts received.	N/A	Yes	N/A	
Downstream PLOAM message count	O	Count of PLOAM messages sent by OLT CT, received by ONU, either broadcast or directed to the specific ONU-ID.	Yes	Yes	Yes (broadcast)	
System_Profile message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Channel_Profile message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Burst_Profile message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Assign_ONU-ID message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Ranging_Time message count	M	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	Mandatory as it provides a base for transmission time drift estimation
Protection_Control message count	M	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by:			Notes
			Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	
Adjust_Tx_Wavelength message count	M	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	Mandatory as it provides a base for wavelength drift estimation (together with the following parameter)
Wavelength dithering Adjust_Tx_Wavelength message count	O	Count of PLOAM messages generated by the wavelength dithering process and sent by OLT CT.	N/A	Yes	Yes	Optional, applies if the wavelength dithering is in place
Adjust_Tx_Wavelength adjustment amplitude	M	An estimator of the absolute value of the transmission wavelength adjustment.	Yes	Yes	N/A	
Unsatisfied Adjust_Tx_Wavelength requests	O	Adjust_ Tx_Wavelength requests not applied or partially applied due to target US wavelength being out of Tx tuning range.	Yes	N/A	N/A	
Deactivate_ONU-ID message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Disable _Serial_Number message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Request_Registration message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	N/A	
Assign_Alloc-ID message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	N/A	
Key_Control message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	
Sleep_Allow message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	
Tuning_Control message count, Request operation code	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU_i	OLT CT	Notes
Tuning_Control message count, Complete_d operation code	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	
Calibration_Request message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Power_Consumption_ Inquire message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	
Reboot_ONU message count	O	Count of PLOAM messages sent by OLT CT	Yes	N/A	Yes	
Bonded_Channel_Stat us message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	Yes	
Get_Set_Capabilities message count	O	Count of PLOAM messages sent by OLT CT	Yes	Yes	N/A	
Upstream PLOAM message count	O	Count of messages (other than Acknowledgement) sent by ONU, received by OLT CT.	Yes	Yes	Yes	
Serial_Number_ONU message count	O	Count of PLOAM messages sent by ONU	Yes	Yes (Note 2)	Yes	
Registration message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Key_Report message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Acknowledgement message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Sleep_Request message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Tuning_Response message count, ACK/NACK operation codes	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Tuning_Response message count, Complete_u/Rollback operation codes	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Power_Consumption _Report message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	Yes	
Bonded_Channel_Res ponse message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	Yes	
ONU_Capabilities message count	O	Count of PLOAM messages sent by ONU	Yes	Yes	N/A	
Activation PM						

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	Notes
Non-discernible activation attempts	O	Quiet window bursts from which the OLT CT is unable obtain the sender's SN.	N/A	N/A	Yes	
Foreign activation attempts	O	Unrecognized SN	N/A	N/A	Yes	
Successful new activations	O	ONU calibrated; requires ONU-ID assignment and ranging.	N/A	Yes	Yes	
Successful pre-configured TWDM channel handovers	O	ONU calibrated, pre-ranged; downstream and upstream wavelength channels set in advance with Protection_Control PLOAM message.	N/A	Yes	Yes	
Successful discretionary TWDM channel handovers	O	ONU retunes to the channel of its choice. ONU calibrated, pre-ranged	N/A	Yes	Yes	
Tuning Control PM (for detailed failure condition codepoint explanation see clause 17.3.2)						
Tuning control requests for Rx only or Rx and Tx	M	Count of PLOAMd Tuning_Control (Request) messages for Rx or Tx/Rx	Yes	Yes	Yes	Locally recognized events
Tuning control requests for Tx only	M	Count of PLOAMd Tuning_Control (Request) messages for TX	Yes	Yes	Yes	Locally recognized events
Tuning control requests rejected on internal condition (not ready to start transceiver tuning by specified time)	M	Count of PLOAMu Tuning_Response(NACK) messages with Response Code = INT_SFC	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on target downstream wavelength channel inconsistency	M	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_xxx	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on downstream administrative label inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_ALBL	Yes	Yes	Yes	Local for ONU; Response code for OLT CT

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	Notes
Tuning control requests rejected on void downstream wavelength channel descriptor	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_VOID	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on channel partition violation	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_PART	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected due to target DS wavelength channel being out of Rx tuning range.	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_TUNR	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on downstream line rate inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_LNRT	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on downstream line code inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = DS_LNCD	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on target upstream wavelength channel inconsistency	M	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_xxx	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on upstream administrative label inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_ALBL	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on void upstream wavelength channel descriptor	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_VOID	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected due to target US wavelength channel being out of Tx tuning range.	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_TUNR	Yes	Yes	Yes	Local for ONU; Response code for OLT CT

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	Collected by: OLT CT for each ONU$_i$	Collected by: OLT CT	Notes
Tuning control request rejected due to insufficient calibration accuracy	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_CLBR	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on upstream optical link type inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_LKTP	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on upstream line rate inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_LNRT	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on upstream line code inconsistency	O	Count of PLOAMu Tuning_Response(NACK) messages with ResponseCode = US_LNCD	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests fulfilled with ONU reacquired at target channel	M	OLT CT: Tuning_Control (Request) PLOAM messages sent, for which ICTP handover closure has been indicated. ONU: Tuning_Control (Request) PLOAM messages received, for which US tuning confirmation has been obtained in the specified target channel.	Yes	Yes	Yes	Local for ONU; ICTP-based at OLT CT.
Tuning control requests failure reason: target DS wavelength channel not found.	M	Timer TO4 expiration in DS Tuning state (O8) in the target channel	Yes	N/A	N/A	Local for ONU
Tuning control requests failure reason: no tuning feedback in target US wavelength channel.	M	Timer TO5 expires in US Tuning state (O9) in the target channel.	Yes	N/A	N/A	Local for ONU
Tuning control requests resolved with ONU reacquired at discretionary channel	M	ONU fails to retune to the specified target channel, but retunes to the channel of its choice.	Yes	Yes	Yes	Local for ONU; ICTP-based at OLT CT.

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	Notes
Tuning control requests failed with ONU Rollback due to communication condition	M	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = COM_DS	Yes	Yes	Yes	Local for ONU and OLT CT
Tuning control requests failed with ONU Rollback due to downstream target wavelength channel inconsistency	M	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = DS_xxx	Yes	Yes	Yes	Local for ONU and OLT CT
Tuning control requests failed with ONU Rollback on downstream administrative label inconsistency	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = DS_ALBL	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests failed with ONU Rollback on downstream optical link type inconsistency	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = DS_LKTP	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests failed with ONU Rollback due to upstream target wavelength channel parameter violation.	M	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_xxx	Yes	Yes	Yes	Local for ONU and OLT CT
Tuning control requests failed with ONU Rollback on upstream administrative label violation	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_ALBL	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on void upstream wavelength channel descriptor	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_VOID	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on Tx tuning range violation.	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_TUNR	Yes	Yes	Yes	Local for ONU; Response code for OLT CT

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	Notes
Tuning control requests rejected on upstream optical link type violation.	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_LKTP	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on upstream line rate violation	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_LNRT	Yes	Yes	Yes	Local for ONU; Response code for OLT CT
Tuning control requests rejected on upstream line code violation	O	Count of PLOAMu Tuning_Response (Rollback) messages with ResponseCode = US_LNCD	Yes	Yes	Yes	Local for ONU and OLT CT
Tuning control requests failed with ONU reactivation	M	Count of state transitions from O5.2 to O8 followed by expiration of timer TO4 or timer TO5, thus causing a transition to O1state	Yes	N/A	N/A	Local for ONU
Power Levelling PM						
Change_Power_Level messages rejected due to Parameter Error	O	Count of Change_Power_Level PLOAM messages acknowledged with Parameter Error Completion code	Yes	Yes	Yes	
Change_Power_Level messages without completion acknowledgement	O	Count of Change_Power_Level PLOAM messages acknowledged with Busy Completion code, but for which no acknowledegment with OK completion code is received.	Yes	Yes	Yes	
OMCI PM						
OMCI baseline message count	O	OMCI message count	Yes, messages directed to the given ONU.	Yes	N/A	
OMCI extended message count	O	OMCI message count	Yes, messages directed to the given ONU.	Yes	N/A	

Table 14-1 – Performance monitoring counters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each wavelength channel	OLT CT for each ONU$_i$	OLT CT	Notes
Autonomous messages	O	OMCI message count	No	Yes	No	
OMCI MIC errors	O	Count of received OMCI messages with MIC errors	Yes	Yes	N/A	
NOTE 1 – The BIP-32 error count is used to obtain a BER estimate only when FEC is off. NOTE 2 – The OLT CT assigns the ONU-ID and updates the per-ONU count only after recognizing the ONU's serial number.						

Table 14-2 – Performance monitoring parameters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each TWDM channel	OLT CT for each ONU$_i$	OLT CT	Notes
Power Monitoring						
Transmit Optical power level	M	Depending on the network configuration (e.g., integrated vs. external WM, presence of RE), the maintained value refers to one of four reference points: S/R, S/R-CP, S/R-CG, or S'/R'. An integer representing a logarithmic power measure having 0.1 dB granularity with respect to −30 dBm (i.e., the value zero represents −30 dBm)	N/A	N/A	Yes	
Energy conservation						
Overall reference interval with respect to which the following parameter is maintained	O	Overall reference interval. 64-bit integer representing time rounded to 1 ms.	Yes	Yes	N/A	
Time spent in the OLT CT Awake Free state.	O	Time spent in a specific low-power state. 64-bit integer representing time rounded to 1 ms.	No	Yes	N/A	
Time spent in the OLT CT Low Power Watch state	O	Time spent in a specific low-power state. 64-bit integer representing time rounded to 1 ms.	No	Yes	N/A	

Table 14-2 – Performance monitoring parameters

Parameter	Mandatory or optional	Description	Collected by: Each ONU for each TWDM channel	Collected by: OLT CT for each ONU_i	Collected by: OLT CT	Notes
Time spent in the ONU Low Power state	O	Time spent in a specific low-power state. 64-bit integer representing time rounded to 1 ms.	Yes	No	N/A	

14.2 Defects

This clause captures the required actions that are performed in the ComTC layer, as opposed to those left to the discretion of an implementer. In particular, the effects of repeated defects of the same type are an implementation matter.

14.2.1 Items detected at OLT channel termination

Table 14-3 summarizes defects detected at the OLT CT.

Table 14-3 – Defects detected at the OLT CT

Type		Description: Detection conditions	Description: Actions	Description: Cancellation conditions	Description: Actions
LOB_i	Loss of burst for ONU_i	Failure to delineate, for any reason, the specified number, $Clob_i$, of consecutive scheduled bursts from ONU_i when not exempt by power management state machine. (Replaces conditions previously known as LOSi and LOFi.) The $Clob_i$ threshold is configurable. Under normal conditions, it defaults to four missing consecutive bursts; however, under certain circumstances (such as power saving purposes), this threshold should be kept as a specific counter and set by the OLT CT to the ONU as according to actual number of tolerated missing bursts.	At the discretion of the OLT CT; may include waiting extra soak time; changing the allocation schedule; deactivating or disabling the offending ONU, or executing a rogue ONU diagnostic procedure. Reporting of the LOB_i condition should be qualified by any DG received.	A scheduled burst from ONU_i successfully received.	

Table 14-3 – Defects detected at the OLT CT

Type		Description			
		Detection conditions	**Actions**	**Cancellation conditions**	**Actions**
LOS	Loss of signal	The OLT CT did not receive any expected transmissions in the upstream (complete PON failure) for four consecutive frames.	At the discretion of the OLT CT; may require additional diagnostic to determine whether PON has been lost, and ultimately lead to protection switching event.	When the OLT CT receives at least one upstream transmission.	–
TIWi	Transmission interference warning for ONU *i*	The ONU transmission drift exceeds the outer (TIW) threshold, and remains outside the threshold after three consecutive attempts to correct it with a Ranging_Time PLOAM message.	At the OLT CT discretion; may include deactivating or disabling the ONU, or executing a rogue ONU diagnostic procedure.	The ONU transmission drift does not exceed the lower (DOW) threshold.	
SUFi	Start-up failure of ONU_i.	The ranging of ONU_i has failed. The OLT CT detects the ONU's serial number, but the ONU fails to complete the bring-up sequence.	Send Deactivate_ONU-ID PLOAM message.	The ONU is ranged successfully.	
DFi	Disable failure of ONU_i.	The ONU continues to respond to the upstream allocations after an attempt to disable the ONU using its serial number (with one or more Disable_Serial_Number PLOAM messages) which may have been preceded by a failed attempt to deactivate the ONU (with one or more Deactivate_ONU PLOAM messages). Note that the OLT CT can detect this condition only if it continues to provide upstream bandwidth allocations to the ONU.	Mitigating action at OLT CT discretion. May include rogue ONU diagnostic procedures. The offending ONU-ID and the associated Alloc-IDs may have to be blocked from re-allocation.	The offending ONU is successfully re-activated and remains positively controlled, or is prevented from transmitting upstream.	
LOPCi	Loss of PLOAM channel with ONU_i.	Generic defect indicating breakage of the PLOAM protocol: persistent MIC failure in the upstream; lack of acknowledgements or proper PLOAM responses from the ONU. Persistent means that the same irregular condition is observed consecutively at least three times.	Mitigating action at the OLT CT discretion; may include ONU re-authentication, ONU deactivation or disabling, or execution of rogue ONU diagnostic procedures.		–

Table 14-3 – Defects detected at the OLT CT

Type		Description			
		Detection conditions	**Actions**	**Cancellation conditions**	**Actions**
LOOCi	Loss of OMCC with ONU_i	Recognized by the OLT CT's OMCI processing engine (based on the persistent MIC failure in the upstream).	Mitigating action at the OLT CT discretion; may include ONU re-authentication, ONU deactivation or disabling, or execution of rogue ONU diagnostic procedures.		
DOTXi	Drift of transmitter wavelength warning	The number of transmitter wavelength adjustment requests in unit of time and/or estimated amplitude of transmitter wavelength adjustment requests exceed the configured thresholds. Note that thresholds should take into account whether the ONU is under closed-loop wavelength locking control.	Mitigating action at the OLT CT discretion; may include ONU re-authentication, ONU deactivation or disabling, or execution of rogue ONU diagnostic procedures.		
ALRFi	Attenuation level request failure	The OLT CT detects that no received power level change has occurred in response to a Change_Power_Level PLOAM message acknowledged by the ONU.	Mitigating action at the OLT CT discretion; may include ONU re-authentication, ONU deactivation or disabling, or execution of rogue ONU diagnostic procedures.	The OLT CT detects received power level change in response to a Change_Power_ Level PLOAM message acknowledged by the ONU	

14.2.2 Items detected at ONU

Table 14-4 summarizes defects detected at the ONU.

Table 14-4 – Defects detected at the ONU

Type		Description			
		Detection conditions	**Actions**	**Cancellation conditions**	**Actions**
LODS	Loss of downstream synchro-nization.	The ONU downstream synchronization state machine in the Hunt or Pre-Sync states. (See clause 10.1.3.)	Provide necessary visual indication and user-side interface signalling. Execute appropriate transition of the ONU activation state machine.	The ONU downstream synchronization state machine in the Sync or Re-Sync states.	Execute appropriate transition of the ONU activation state machine.

14.2.3 Urgent ONU status snapshot record

To facilitate post-mortem diagnostics, the ONU supports recording a snapshot of relevant ONU status information, defects and failure conditions. The information is collected and stored by the ONU when communication channel with the OLT CT is compromised or unavailable.

The urgent status snapshot record is made as a part of the dying gasp (DG) sequence, and any time the transmitter is being switched off by the ONU software. It can be retrieved either remotely on site or in the lab upon ONU replacement. The urgent status snapshot record is stored in non-volatile memory to ensure it survives ONU reactivation, warm and cold reboot, power cycle, and power loss.

The storage is expected to accommodate at least ten urgent status snapshot records and to be reasonably protected against accidental erasure and unauthorized access.

15 Security

This clause discusses threat models characteristic for the operating environment, and specifies authentication, data integrity, and privacy protection aspects of the system.

15.1 Threat model

HSP security is intended to protect against the following threats:

1) Since downstream data is broadcast to all ONUs attached to the OLT CT, a malicious user capable of replacing or re-programming an ONU would be capable of receiving all downstream data intended for all connected users.
2) Since upstream data received by the OLT CT can originate from any ONU attached to the optical distribution network (ODN), a malicious user capable of replacing or re-programming an ONU could forge packets so as to impersonate a different ONU (i.e., theft of service).
3) An attacker could connect a malicious device at various points on the infrastructure (e.g., by tampering with street cabinets, spare ports or fibre cables). Such a device could intercept and/or generate traffic. Depending on the location of such a device, it could impersonate an OLT CT or alternatively it could impersonate an ONU.
4) A malicious user in any of the above scenarios could record packets transmitted on the PON and replay them back onto the PON later, or conduct bit-flipping attacks.

PONs are deployed in a wide variety of scenarios. In some cases, the ODN, the optical splitter, or even the ONUs may be installed in a manner considered to be physically secure or tamper-proof.

To accommodate these scenarios in an economical manner, activation of some of the security features is optional, as indicated in the clauses below.

15.2 Authentication

The HSP system supports three mechanisms for authentication. The first mechanism is based on the use of Registration_ID. It is executed in the course of ONU activation and may be repeated throughout the duration of the activation cycle, i.e., until the ONU's next entry into the Initial state (O1). When an ONU is handed over from the source OLT CT to the target OLT CT, the target OLT CT may authenticate the ONU by issuing a Request_Registration PLOAM message. The registration-based authentication mechanism provides a basic level of authentication of the ONU to the OLT CT. It does not provide authentication of the OLT CT to the ONU. Support of the registration-based authentication mechanism is mandatory in all HSP devices. The two other authentication mechanisms provide secure mutual authentication to both OLT CT and ONU. One of them is based on an ONU management and control interface (OMCI) message exchange (see Annex C). The other is based on an IEEE 802.1X message exchange and provides a wide range of extensible features (see Annex D). Support for OMCI-based and IEEE 802.1X-based authentication mechanisms is mandatory for implementation at the component level, but optional from an equipment specification perspective.

In other words, the ComTC layer implementation will have the capability to support both secure mutual authentication methods, but equipment constructed using these ComTC-layer implementations may choose not to support them.

It is within the discretion of an operator to require support of one or both secure mutual authentication mechanisms at the equipment specification stage, and to employ any or none of the authentication methods, including the basic registration-based authentication, when the system is in service.

Upon authentication failure, the OLT CT may undertake measures to restore functionality and to prevent a potential security breach, which may include repeating authentication using the same or an alternative mechanism, blocking upstream and downstream traffic, deactivating or disabling the offending ONU, or executing the rogue ONU diagnostic procedures.

15.2.1 Registration-based authentication

The registration-based authentication mechanism can provide authentication of ONU to OLT CT, but not vice versa. Its support is mandatory for all HSP systems. To maintain full functionality, this method requires:

– that a Registration_ID be assigned to a subscriber at the management level;

– that the Registration_ID be provisioned into the OLT CT and be communicated to the field personnel or to the subscriber directly;

– that the ONU support a method for entering the Registration_ID in the field (specification of such a method being beyond the scope of this Recommendation);

– that the field personnel or the subscriber in fact enter the Registration_ID into the ONU.

The Registration_ID is stored at the ONU in a non-volatile storage. It is retained through ONU re-activation and power cycle, until explicitly reset by the field personnel or the subscriber.

15.2.1.1 The OLT CT perspective

The OLT CT must support ONU authentication based on the reported Registration_ID, as well as the MSK and derived shared key calculation procedure based on the reported Registration_ID (see clause 15.3).

The OLT CT requests the Registration_ID from the ONU in the following situations:

– In the course of ONU activation, by issuing a ranging grant.

– As a final handshake upon completion of a secure mutual authentication procedure, by sending a Request_Registration message to the ONU.

– At any time throughout the ONU's activation cycle at its own discretion, by sending a Request_Registration message to the ONU.

If at the time of Registration_ID receipt from the ONU, there is no valid secure mutual association (SMA) between the OLT CT and the ONU (i.e., in the course of ONU activation, or if secure mutual authentication has not been executed or has failed), the OLT CT:

– must compute the master session key (MSK) and derived shared keys based on the reported Registration_ID;

– may perform authentication of the ONU based on the reported Registration_ID.

It is up to the operator to specify whether registration-based authentication is performed and how the result is used. Failure of registration-based authentication shall not prevent the OLT CT from issuing an equalization delay to the ONU (i.e., the ONU is nevertheless allowed to enter the Operation state (O5)) or from maintaining management level communication with the ONU, but may have an effect on how the OLT CT further handles the ONU and, in particular, on subsequent provisioning of services.

Registration-based authentication is not performed and the registration-based MSK and derived shared keys are not calculated, if at the time of the Registration_ID report there exists a valid SMA between the OLT CT and the ONU.

Once the OLT CT transmits a Request_Registration message to the ONU while expecting to use the reported Registration_ID for shared key derivation, it refrains from sending to that ONU other PLOAM or OMCI messages with ONU-specific MIC (see clauses 15.3.2 and 15.3.3) until after the Registration_ID is received and the registration-based MSK and derived shared keys are calculated.

Once the OLT CT completes calculation of the registration-based MSK and derived shared keys for a particular ONU, it immediately commits those keys as active.

At the start of the ONU's activation cycle, the OLT CT discards any active registration-based MSK and derived shared keys.

15.2.1.2 The ONU perspective

The ONU must be able to perform calculation of the MSK and derived share keys based on the Registration_ID.

The ONU computes the registration-based MSK and derived shared keys upon power up (initially, using the well-known default Registration_ID (see clause 11.3.4.2)), and each time the Registration_ID changes. The computed values are stored for future use. As the registration-based key set may be required at any time, the ONU may benefit by storing the registration-based MSK and derived shared keys separately from the MSK and derived shared keys based on secure mutual authentication.

ONU reports Registration_ID to the OLT in the following situations:

– In the course of ONU activation, in response to a ranging grant.
– At any time during the ONU's activation cycle, in response to a Request_Registration message.

The events that cause registration-based key re-computation are asynchronous to the physical layer operations, administration and maintenance (PLOAM) channel events. The ONU is expected to have the registration-based MSK and derived shared keys available at the time it reports its Registration_ID to the OLT CT.

If there is no valid SMA between the OLT CT and the ONU, the ONU commits the set of shared keys based on the reported Registration_ID immediately upon sending the Registration PLOAM message.

The ONU retains the Registration_ID and the stored registration-based MSK and derived shared keys between activation cycles and between power cycles.

15.2.2 Secure mutual authentication options

Two secure mutual authentication mechanisms are defined: OMCI-based authentication (Annex C), and IEEE 802.1X-based authentication (Annex D). These mechanisms authenticate the OLT CT to the ONU as well as the ONU to the OLT CT. The support of both secure mutual authentication mechanisms is optional on the system level.

If secure mutual authentication is supported by the system and is employed by the operator, the OLT CT initiates the secure mutual authentication procedure using an appropriate mechanism upon completion of the ONU activation procedure before user data traffic is transmitted, and subsequently may initiate re-authentication at any time, subject to the operator's policies and discretion.

In the course of execution of a secure mutual authentication procedure, the OLT CT and the ONU compute the secure master session key (MSK) and a set of secure shared keys applicable for specific management and operation tasks.

Both the OLT CT and the ONU discard the MSK and derived shared keys obtained in the course of secure mutual authentication at the start of the ONU's activation cycle along with the other ComTC layer parameters.

15.3 Key derivation

The mathematical details of the MSK and derived shared key calculation are shared by the OLT CT and the ONU.

The ONU computes the registration-based MSK and derived shared keys upon power up (initially using the well-known default Registration_ID (see clause 11.3.4.2)), and each time the Registration_ID changes.

The OLT CT computes the registration-based MSK and derived shared keys under the following conditions:

1) Each time the ONU reports its Registration_ID to the OLT CT in response to a ranging grant in the course of ONU activation, regardless of whether or not the reported Registration_ID is used for authentication, and what the outcome of the registration-based authentication procedure is.
2) Each time the ONU reports its Registration_ID to the OLT CT in response to the Request_Registration PLOAM message, but only when there is no valid mutual security association between OLT CT and ONU.

Both the OLT CT and the ONU compute the secure MSK and derived shared keys each time a secure mutual authentication procedure using either the OMCI-based or the IEEE 802.1X-based mechanism is executed.

15.3.1 Cryptographic method

The secure key derivation procedure employs the cipher-based message authentication code (CMAC) algorithm specified in [NIST SP800-38B], applied with the configured bit block cipher. The default cipher is the advanced encryption standard (AES) encryption algorithm [NIST FIPS-197] with 128 bit key length. The use of additional ciphers (both algorithm and key length) can be configured via the OMCI. Before OMCI configuration occurs, the default cipher will be used. When the cipher selection is changed, the derived keys will have to be recalculated using the new cipher. The key derivations function below refers to the block cipher applied by the CMAC algorithm as "BC" and key length "*Tlen*" for generality.

The BC-CMAC function takes as its inputs:

– block cipher key K;
– the information message M; and
– the bit length of the output *Tlen*,

and produces the secret key as a message authentication code T of length *Tlen* as an output. The notation for invocation of the extended BC-CMAC function (BC-ECMAC) is:

$$T = \text{BC-ECMAC}(K, M, Tlen) = \text{BC-CMAC}(K, M, Tlen) \text{ when } Tlen <= 128$$

$$T = \text{BC-ECMAC}(K, M, Tlen) = \text{BC-CMAC}(K, (\text{MlessLastBlock}), 128) \mid \text{BC-CMAC}(K, \text{M}, 128) \text{ when } Tlen = 256 \quad (15\text{-}1)$$

If Tlen is 128 bits, the BC-ECMAC is the simple CMAC function. If Tlen is 256 bits, then the BC-ECMAC is a concatenation of the penultimate CMAC block and the final CMAC block. The information message of the penultimate CMAC block is the information message M of the final CMAC block from which the last 128-bit block is truncated.

15.3.2 Master session key

The master session key (MSK) is a 128 or 256-bit value that is shared between the OLT CT and the given ONU as a result of an authentication procedure and which serves as a starting point for the derivation of all of the other secret keys used in subsequent secure communications.

For the registration-based key derivation, the MSK is obtained from the ONU Registration_ID:

$$\text{MSK} = \text{AES-CMAC}((0\text{x}55)_{16}, \text{Registration\_ID}, 128) \quad (15\text{-}2)$$

Note that the cipher is always AES-128 for the registration-based method. Here $(0\text{x}55)_{16}$ denotes a default key composed of the hex pattern 0x55 repeated 16 times, and Registration_ID is the 36-byte value transmitted in the Registration PLOAM message. Note that the Registration PLOAM message may carry either an ONU-specific Registration_ID, or a well-known default value.

When the key derivation is triggered by the success of secure mutual authentication, the procedure to obtain the MSK depends on the specific authentication mechanism. (see clauses 9.13.11 of [ITU-T G.988] for OMCI-based mutual authentication and Annex D of [ITU-T G.987.3] for IEEE 802.1X-based mutual authentication).

In case 256-bit cipher is selected and only 128-bit MSK is available (e.g., after registration-based authentication or as a result of mutual authentication), a 256-bit MSK is derived using equation (15-1) and the AES-128 cipher. In the penultimate CMAC block the default key $(0\text{x}55)_{16}$ is used in case of registration-based authentication and pre-shared key (PSK) is used in case of mutual authentication.

15.3.3 Derived shared keys

The session key (SK) binds the MSK to the context of the security association between the OLT CT and ONU. The SK, which is used for subsequent key derivations, is obtained using the following formula:

$$\text{SK} = \text{BC-ECMAC}(\text{MSK}, (\text{SN} \mid \text{PON-TAG} \mid \text{PON-TAG} \mid \text{SN}), \text{Tlen}) \quad (15\text{-}3)$$

where the information message, which is 32 bytes long, is a concatenation of four elements: the ONU serial number (SN) as reported in octets five to 12 of the upstream Serial_Number_ONU PLOAM message (clause 11.3.4.1), the PON-TAG as reported in octets 26 to 33 of the downstream Burst_Profile PLOAM message (clause 11.3.3.1) repeated twice, and the SN once again.

The OMCI integrity key (OMCI_IK) is used to generate and verify the integrity of OMCI messages. The OMCI_IK is derived from the SK by the following formula:

$$\text{OMCI\_IK} = \text{BC-ECMAC}(\text{SK}, \text{"OMCIIntegrityKeyMakeOMCImoreSafe"}, \text{Tlen}) \quad (15\text{-}4)$$

Here the information message parameter of the BC-ECMAC function is 256 bits long and is the ASCII string "OMCIIntegrityKeyMakeOMCImoreSafe".

The PLOAM integrity key (PLOAM_IK) is used to generate and verify the integrity of FS layer unicast PLOAM messages. The PLOAM_IK is derived from the SK by the following formula:

$$\text{PLOAM\_IK} = \text{AES-CMAC}(\text{SK}, 0\text{x}504\text{c}4\text{f}414\text{d}496\text{e}7465677274794\text{b}6579, 128) \quad (15\text{-}5)$$

Here the information message parameter of the AES-CMAC function is 128 bits long, and is the hexadecimal representation of the ASCII string "PLOAMIntegrtyKey". In case of 256-bit SK, the SK value in (15-5) is the 128 LSBs of the SK (the value computed using equation (15-3)).

For downstream broadcast PLOAM messages and for unicast PLOAM messages exchanged in the course of ONU activation prior to availability of the registration-based MSK, the default PLOAM_IK value is used, which is equal to $(0\text{x}55)_{16}$, the subscript indicating the multiplicity of repetition of the specified hex pattern.

The key encryption key (KEK) is used to encrypt/decrypt and protect/verify the integrity of the data encryption key that is carried in the PLOAM channel. The KEK is derived from the SK by the following formula:

KEK = BC-ECMAC(SK, "KeyEncryptionKeyMakeKEKMoreSafey", Tlen) (15-6)

Here the information message parameter of the BC-ECMAC function is 32 bytes long and is the ASCII string "KeyEncryptionKeyMakeKEKMoreSafey".

An ONU re-derives the SK, the OMCI_IK, the PLOAM_IK and the KEK when the PON-TAG in the downstream Burst_Profile PLOAM message changes or when the cipher selection is changed. The PON-TAG may change in the course of burst profile update or ONU handover from the source OLT CT to the target OLT CT.

15.4 XGEM payload encryption system

XGEM payloads can be encrypted for transmission to provide data privacy in the presence of a potential eavesdropping threat.

15.4.1 Cryptographic method

The default algorithm used for XGEM payload encryption is the AES-128 [NIST FIPS-197] cipher, used in Counter mode (AES-CTR), as described in [NIST SP800-38A]. Cipher algorithms AES-128 (mandatory), AES-256 (mandatory), Camellia-128, Camellia-256, and SM4(-128) [ISO/IEC 18033-3:2010] can be configured via the OMCI, as defined in clause 9.1.2 [ITU-T G.988]. The configured cipher algorithm is used for both upstream and downstream, unicast and multicast. The CTR algorithm applies a forward cipher with a secret key known only to the OLT CT and ONU (or ONUs – in the case of a broadcast key) to a sequence of input counter blocks to produce a sequence of output blocks that are exclusive-OR-ed with the plaintext XGEM payload. The sequence of counter blocks is initialized for each XGEM frame payload field to a value called "initial counter block" and is incremented using a standard incrementing function applied to the entire counter block (see clause B.1 of [NIST SP800-38A]). To decrypt the ciphertext, for each XGEM frame, the forward cipher with the same secret key is applied to a sequence of input counter blocks initialized to the same initial counter block value. The output blocks are exclusive-OR-ed with the blocks of ciphertext XGEM payload to restore the plaintext XGEM payload.

15.4.2 Secret key selection

XGEM payload encryption may apply to any unicast transmission in the downstream and the upstream directions, and to one specified multicast service stream for downstream broadcast transmission. The OLT CT ensures that, at all times, there is a PON-wide broadcast key pair which is used for broadcast XGEM Port-ID or Port-IDs, and that there is a unicast key pair for each ONU which is used for all XGEM Port-IDs that belong to that ONU. See clause 15.5 for the key exchange and activation mechanism that, at all times, allows to select a valid key for each supported key pair.

The key pair to be used for XGEM payload encryption depends on the XGEM Port-ID. Given the XGEM Port-ID (unicast or broadcast), the sender selects the specific key of the appropriate key pair, according to the rules of clause 15.5, and provides an indication of the selected key in the XGEM header.

Each XGEM frame header, as defined in clause 9.1.2, contains a 2-bit field designated as the key index, carrying an indication whether or not the particular XGEM frame payload is encrypted and if so, which of the encryption keys was used. The following code points are defined for the key index field:

– 00 – XGEM frame payload is unencrypted;
– 01 – XGEM frame payload is encrypted using the first encryption key;
– 10 – XGEM frame payload is encrypted using the second encryption key;

– 11 – Reserved.

15.4.3 Initial counter block

The 128-bit initial counter block value for a particular XGEM frame is determined by the values of superframe counter (SFC) and intra-frame counter (IFC) associated with the given XGEM frame.

In the downstream direction, the SFC value is contained in the PSBd field of the PHY frame in which the given downstream XGEM frame is transmitted. In the upstream direction, the SFC value is contained in the PSBd field of the PHY frame that specifies the upstream PHY burst in which the given upstream XGEM frame is transmitted. For the purpose of the initial counter block construction, the most significant three bits of the SFC value is omitted, and the 48-bit field is used.

To obtain the IFC value of the given XGEM frame, the following block enumeration procedure applies (see Figure 15-1).

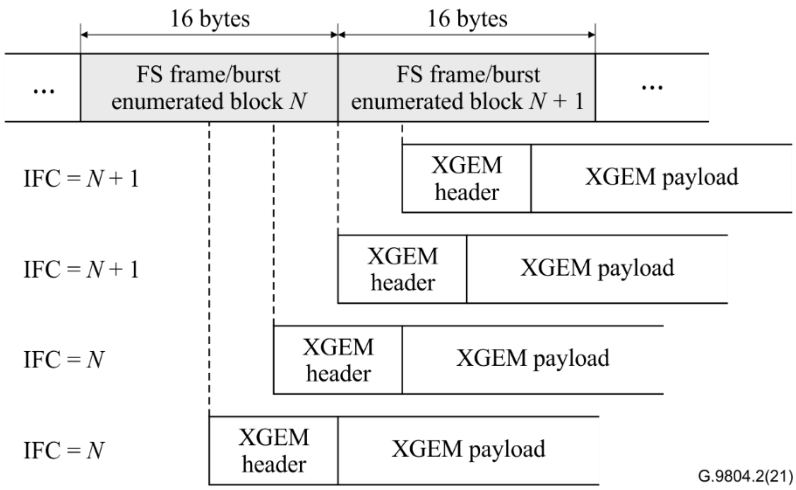


Figure 15-1 – Obtaining the intra-frame counter value for an XGEM frame

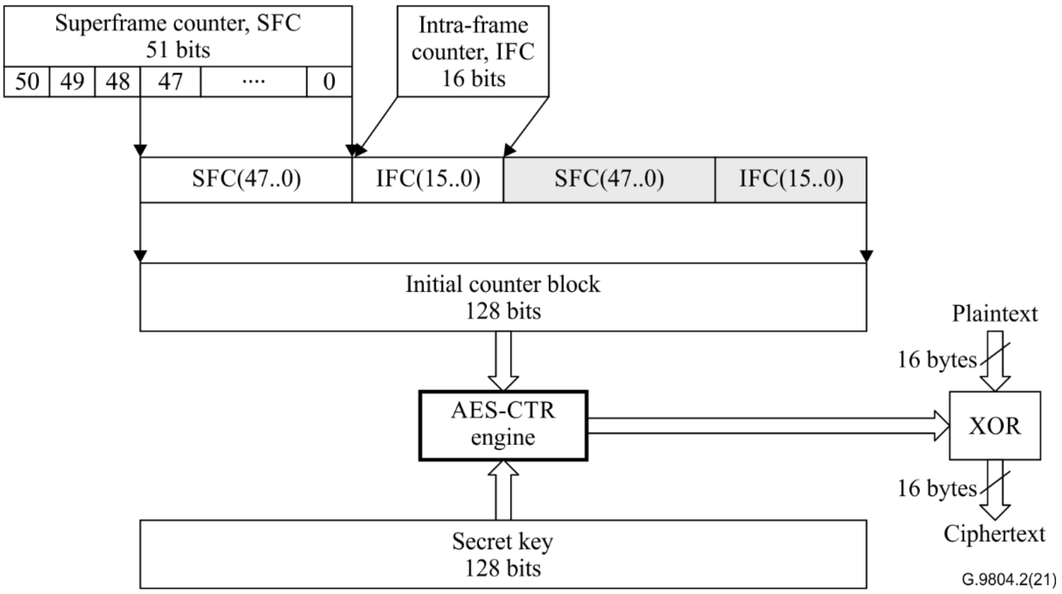
In the downstream direction, the FS frame of the framing sublayer (see Figure 8-1) is partitioned into 16-byte blocks, and the last block could be incomplete. These blocks are sequentially numbered from 0. The downstream FS frame size is shown in Table 8-1. The size of the sequence number is 16 bits.

In the upstream direction, the FS burst of the framing sublayer (see Figure 8-5) is partitioned into 16-byte blocks, and these blocks are sequentially numbered from S to (S+X). Here S=StartTime*ϕ, and X is the number of complete and incomplete 16-byte blocks in the FS burst, less 1. The size of the sequence number is 16 bits. The largest possible 16-byte block number in an upstream burst is determined by the FS burst specification constraint (see clause 8.1.3):

$$S+X = (\text{StartTime} + \Sigma_n \text{GrantSize}_n) \times \phi < \mathbf{2}^{16}$$

An XGEM frame appearing within the payload of a downstream FS frame or upstream FS burst can occur in one of four phase positions with respect to the 16-byte block boundary. The IFC of an XGEM frame is the sequence number of the 16-byte block to which the first 4 bytes of the XGEM header belong.

The 128-bit initial counter block for a particular downstream XGEM frame is a concatenation of SFC and IFC for the given frame obtained, as described above, concatenated with itself. The 128-bit initial counter block for a particular upstream XGEM frame is a concatenation of SFC and IFC for the given frame obtained, as described above, concatenated with the bit-complement of itself.



NOTE – For upstream, the shaded fields are taken in bit-complement.

Figure 15-2 – Initial counter block construction for downstream encryption

NOTE – It has been shown that two SFC(47..0) values, $0b1(0)_{47}$ and $0b0(1)_{47}$, can lead to several duplicated counter blocks in the upstream and downstream directions. As these values appear at the middle of the SFC(47..0) range, the window of weaker counter blocks occurs for approximately 250 μs once in 1000 years. The potential impact can be mitigated by initializing the SFC to a small value.

15.5 Data encryption key exchange and activation mechanism

15.5.1 Overview

The data encryption configuration of an ONU is provisioned using OMCI. Each ONU advertises its security capabilities, which are required to include at least AES-128 and AES-256. The OLT is free to select zero or any one of the ONU's advertised capabilities; the OLT CT's choice then becomes binding on the ONU. For each non-default XGEM port, the OLT CT configures the port's encryption key ring attribute (GEM port network CTP managed entity, clause 9.2.3 of [ITU-T G.988]), which specifies whether the port is provisioned for encryption, and if so, in which direction encryption applies (downstream only or both downstream and upstream), and which data encryption key type (unicast or broadcast) should be used for the encrypted traffic. The default XGEM port has no configurable key ring, and is defined for bidirectional encryption using the unicast type key.

Provisioning a non-default XGEM port for encryption does not imply the traffic is always encrypted. The encryption status of each individual XGEM frame is determined dynamically by the sender, within the explicitly configured or pre-defined capabilities of the associated XGEM port, and is indicated in the XGEM frame header.

Whenever the default XGEM port traffic is encrypted in the downstream direction, the ONU is expected to encrypt the default XGEM port traffic upstream.

For each of the two key types (unicast and broadcast), both the OLT CT and the ONU maintain an indexed array of two data encryption key entries. The broadcast keys are generated by the OLT CT and communicated to the ONUs using OMCI as described in clause 15.5.4. The unicast keys are generated and communicated upstream by the ONU upon the OLT CT's instructions using the PLOAM channel as described in clause 15.5.3. The value of the unicast key is not exposed to the OMCI.

The type of the data encryption key used to encrypt the payload of a particular XGEM frame on transmission is implicit in the XGEM Port-ID. The Key_Index field of the XGEM frame header indicates whether the payload is encrypted and, if so, which of the two data encryption keys of the given type is used. The specific key selected for encryption shall be valid at the XGEM frame transmission time, as determined by the respective key exchange protocol. The sender starts using the new data encryption key during the time interval when both keys of the respective type are valid. When no valid data encryption key is available (for example, immediately after ONU reactivation), the sender transmits XGEM frames without encryption using a Key_Index value of zero.

15.5.2 Cryptographic method

The data encryption keys (EK) are themselves transmitted between the OLT CT and the ONU encrypted with the selected block cipher which is used in electronic codebook mode (ECB), as specified in [NIST SP800-38A]. The specific calculations are as follows.

For 128 bit key length:

OLTkeyContrib = BC-ECB(KEK, KeyControl_RandomX)

ONUkeyContrib random number of 128 bits generated by the ONU

For 256 bit key length:

OLTkeyContrib = BC-ECB(KEK, KeyControl_RandomX | KeyControl_RandomY)

ONUkeyContrib random number of 256 bits generated by the ONU

where the values KeyControl_RandimX, KeyControl_RandomY are communicated to the ONU in Key_Control message defined in clause 11.3.3.8.

Then the 128-bit EK and 256-bit EK can be calculated using ONUkeyContrib, OLTkeyContrib of 128 bit and 256 bit length, respectively, as:

EK = BC-ECMAC(KEK, ONUkeyContrib | OLTkeyContrib, Tlen)

where Tlen =128 for 128-bit EK, Tlen=256 for 256-bit EK, and sign | stands for concatenation.

Encrypted EK = BC-ECB(KEK, EK)

In BC-ECB encryption, the selected forward cipherfunction is applied directly and independently to each block of plaintext using a secret key to produce a block of ciphertext. In BC-ECB decryption, the inverse cipherfunction is applied directly and independently to each block of ciphertext with the same secret key to restore the original block of plaintext. The notation for invocation of the BC-ECB encryption and decryption functions are:

$$C = \text{BC-ECB}(K, P);$$

$$P = \text{BC-ECB}^{-1}(K, C);$$

Here P is a block of plaintext, C is a block of ciphertext, and K is the block cipher key. Note that since the ECB method is being used to encrypt unique random numbers, there is no loss of security.

15.5.3 Unicast encryption

The OLT CT and the ONU maintain a number of logical state variables that are associated with the encryption and decryption functions, and this state information guides the exchange and activation of new key material. The OLT CT's key exchange state diagram is shown in Figure 15-4, and the ONU's key exchange state diagram is shown in Figure 15-5. Both of the state machines run entirely in the Operation state (O5). When the ONU is activated or reactivated, the data encryption keys are invalidated and are reacquired via PLOAM exchange after the shared KEK is established.

15.5.3.1 Sequence of encryption key exchange and activation events

The process of unicast data encryption key exchange and activation is performed under the control of the OLT CT by means of a series of PLOAM messages. The causal sequence of associated events is given below:

– The OLT CT begins by requesting a new unicast data encryption key from the ONU by using the Key_Control(Generate) PLOAM message that contains the key index for the new key as well as random numbers suitable for cryptographic purposes. A single copy of the request is sent, and if there is no response, the OLT CT should retry the request.

– Upon receipt of the Key_Control(Generate) PLOAM message from the OLT CT, the ONU generates a new encryption key using a random number generator suitable for cryptographic purposes as deyailed above. The ONU stores the new key in its encryption control and decryption control structures (according to the specified key index). The ONU then sends the new key to the OLT CT using the Key_Report(NewKey) PLOAM message. The key is encrypted in the Key_Report(NewKey) PLOAM message with BC-ECB using the KEK.

– When the OLT CT receives the Key_Report(NewKey) PLOAM message, it decrypts the new key and stores it in its logical encryption control and decryption control structures for the originating ONU, according to the specified key index.

– The OLT CT then sends the Key_Control(Confirm) PLOAM message that contains the key index of the newly generated key.

– When the ONU receives the Key_Control(Confirm) PLOAM message, it knows that the OLT CT now has the new key. Therefore, the ONU changes the new key state in the encryption control structure to active. The ONU responds with a Key_Report(ExistingKey) PLOAM message indicating the "Key_Name" of the specified key.

– If, at any time, the OLT CT wishes to check the ONU's key against its own (to diagnose a key mismatch situation), the OLT CT can issue a Key_Control(Confirm) PLOAM message for a Key_Index of an existing key. This triggers the ONU to respond with a Key_Report(ExistingKey) PLOAM message containing the key name.

The preceding description pertains to a normal key exchange process; however, the state diagrams in clauses 15.5.3.2 and 15.5.3.3 are the primary reference for the behaviour.

If on receipt of a Key_Report(ExistingKey) PLOAM message, the OLT CT discovers a discrepancy between the reported and locally computed key hashes, it should stop using the data encryption key with the specified key index and take remediation actions at its own discretion. Such actions may include, for example, reconfirmation of the key, generation of a new key, or re-authentication of the ONU.

Referring to the state diagrams of Figures 15-4 and 15-5, the notational conventions "oldkey" and "newkey" denote the two data encryption keys (with the corresponding key indices), of which the former is active before the key exchange is initiated, and the latter, after the key exchange is completed.

Note that in the course of the key exchange in the view of both the OLT CT and the ONU, the moment the oldkey ceases to be valid for transmit differs from the moment the oldkey ceases to be valid for receive, and the moment the newkey becomes valid for transmit differs from the moment the newkey becomes valid for receive.

For the OLT CT as well as for the ONU, there is a time interval when both oldkey and newkey are valid for transmit, and there is a time interval when both oldkey and newkey are valid for receive. Within the interval when both oldkey and newkey are valid for transmit, the respective sender selects a moment when it starts encrypting the outgoing XGEM frame payload with the newkey and putting the Key_Index of the newkey into the outgoing XGEM frame header. Once the sender switches to using the newkey for transmit, the sender should stop using and discard the oldkey for transmit. Within the interval when both oldkey and newkey are valid for receive, the receiver accepts either Key_Index to decrypts the incoming XGEM frame payload. Outside that interval, the receiver discards the XGEM frame payload that is encrypted with an invalid key.

It is the responsibility of the OLT CT to ensure that the Key_Index parameter of the Key_Control PLOAM messages is set correctly. In particular, the OLT CT should abstain from sending Key_Control(Confirm) PLOAM message for the Key_Index that is presently invalid at the ONU and, except for the key mismatch recovery situations, from sending Key_Control(Generate) PLOAM message for the only currently valid Key_Index at the ONU.

Figure 15-3 illustrates key validity in key exchange.

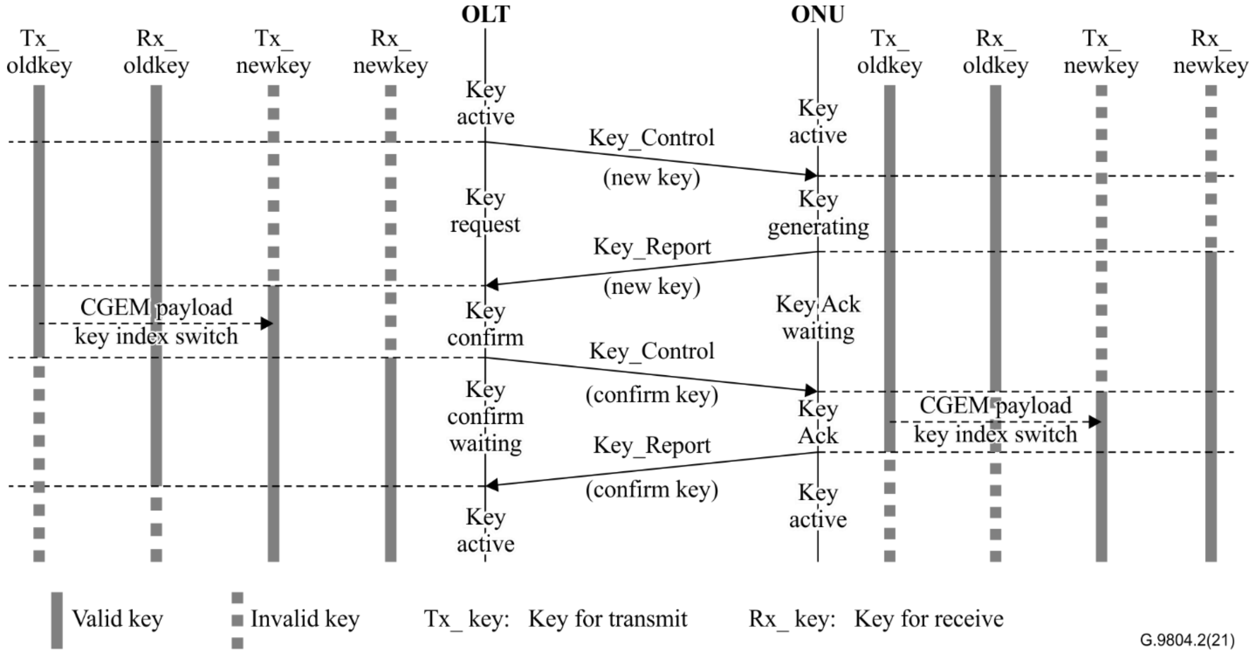


Figure 15-3 – Key validity in key exchange

15.5.3.2 OLT CT states and state diagram

The five OLT CT states of encryption key exchange and activation are defined as follows:

a) Key Inactive state (KL0)

The ONU is registered and is in O5 state. There is no active key for XGEM payload encryption. No keys are valid to receive and/or transmit between the OLT CT and the ONU. When the OLT CT decides to initiate the unicast data encryption key exchange, it moves to the Key Request state (KL1).

b) Key Request state (KL1)

The OLT CT initiates a new key request by sending a Key_Control(Generate) PLOAM message, that instructs the ONU to generate a new key and to send it upstream. In this state, the new key is yet unknown to the OLT CT and, therefore, is invalid to receive and invalid to transmit. If there is an old key (i.e., an existing key), the old key remains valid to receive and valid to transmit at the OLT CT. Once a Key_Report(NewKey) PLOAM message is received, the OLT CT moves to the Key Confirm state (KL2).

If timer TK1 expires and no Key_Report(NewKey) message is received, the OLT CT initiates a new key request.

c) Key Confirm state (KL2)

In this state, the new key is valid to transmit and invalid to receive at the OLT CT. The old key (if there is an old key) is valid to receive and valid to transmit at the OLT CT. The OLT CT selects the moment to begin encrypting XGEM payload with the new key.

d) Key Confirm Waiting state (KL3)

The OLT CT sends a Key_Control(Confirm) PLOAM message for the specified key index. The new key becomes valid to receive and valid to transmit at the OLT CT. The old key (if there is an old key) remains valid to receive but becomes invalid to transmit at the OLT CT. Once a Key_Report(ExistingKey) PLOAM is received, the OLT CT moves to the Key Active state (KL4).

If timer TK2 expires and no Key_Report(ExistingKey) has been received, the OLT CT sends a new Key_Control(Confirm) PLOAM message.

e) Key Active state (KL4)

Once a Key_Report(ExistingKey) PLOAM message is received, the old key (if there is an old key) becomes invalid to receive and invalid to transmit. The new key is the only active key for receive and transmit between the OLT CT and the ONU.

If a rekey is required, the OLT CT moves to the Key Request state (KL1).

If a key check is required, the OLT CT sends a Key_Control(Confirm) PLOAM message, but no state transition occurs.

To support encryption key exchange and activation, the OLT CT maintains three timers:

– TK1 – OLT CT key exchange waiting timer

Timer TK1 is used to abort an unsuccessful key exchange or key check attempt by limiting the overall time an OLT CT can sojourn in states KL1, KL2, and KL3. The recommended initial value of TK1 is 100 ms.

– TK2 – Key waiting timer

Timer TK2 is used to abort an unsuccessful key request attempt by limiting the overall time an OLT CT can sojourn in state KL1. The recommended initial value of TK2 is 10 ms.

– TK3 – Key confirmation waiting timer

Timer TK3 is used to abort an unsuccessful key confirmation request attempt by limiting the overall time an OLT CT can sojourn in state KL3. The recommended initial value of TK3 is 10 ms.

Figure 15-4 shows a graphic representation of the states of the OLT CT.

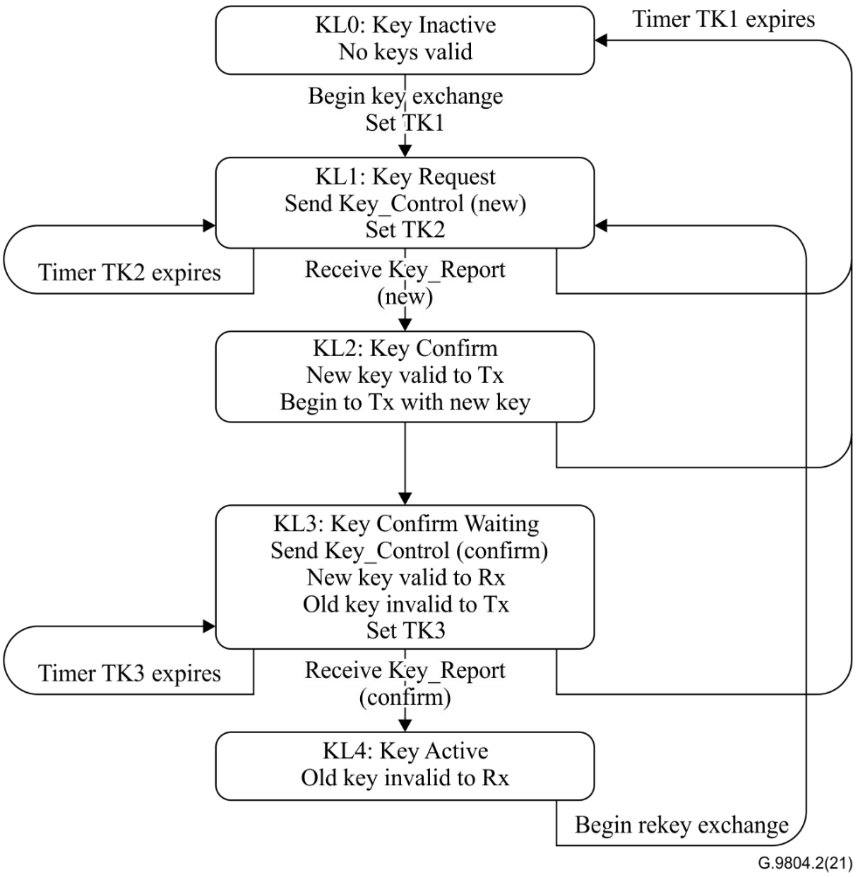


Figure 15-4 – OLT CT key exchange state diagram

15.5.3.3 ONU states and state diagram

The five ONU states of encryption key exchange and activation are defined as follows:

a) Key Inactive state (KN0)

The ONU is registered and is in state O5. There are no active keys for XGEM payload encryption between the OLT CT and the ONU. When a Key_Control(Generate) PLOAM message for a new key is received, the ONU moves to the Key Generating state (KN1).

b) Key Generating state (KN1)

The ONU generates a new key. If there is an old key, the old key is valid to receive and valid to transmit at the ONU. The new key is invalid to receive and invalid to transmit at the ONU.

c) Key Ack Waiting state (KN2)

The ONU sends a Key_Report(NewKey) PLOAM message to inform the OLT CT of the new key. The new key is encrypted for PLOAM transmission with AES-ECB using KEK. The new key becomes valid to receive and remains invalid to transmit at the ONU. Once a Key_Control(Confirm) PLOAM message is received, the ONU moves to the Key Ack state (KN3).

If timer TK5 expires and no Key_Control(Confirm) message is received, the ONU resends the Key_Report(NewKey) PLOAM message with the new key. If the ONU receives a new Key_Control(Generate) PLOAM message, it also resends the Key_Report(NewKey) PLOAM message. In this case it is at ONU's discretion to use a previously generated key, or to generate yet another new key.

d) Key Ack state (KN3)

In this state, the new key is valid to receive and becomes valid to transmit at the ONU. The old key (if there is an old key) remains valid to transmit but becomes invalid to receive at the

ONU. The ONU begins to encrypt XGEM payload with the new key. The ONU acknowledges the OLT CT by sending a Key_Report(ExistingKey) PLOAM message with the Key_Name of the newly generated key. Once the Key_Report(ExistingKey) PLOAM message is sent, the ONU moves to the Key Active state (KN4).

e) Key Active state (KN4)

In this state, the new key is valid to receive and valid to transmit at the ONU. The old key (if there is an old key) becomes invalid to receive and invalid to transmit at the ONU.

Once a Key_Control(Generate) PLOAM message is received for the presently inactive Key_Index, the ONU moves to the Key Generating state (KN1) with the active key being referenced to as old key.

If at any time a Key_Control(Confirm) PLOAM message is received for the existing key, the ONU sends a Key_ Report(ExistingKey) PLOAM message, but no state transition occurs.

To support encryption key exchange and activation, the ONU maintains two timers:

– TK4 – ONU key exchange waiting timer

Timer TK4 is used to abort an unsuccessful key exchange or key check attempt by limiting the overall time an ONU can sojourn in the set of states KN1, KN2, and KN3. The recommended initial value of TK4 is 100 ms.

– TK5 – Key Ack waiting timer

Timer TK5 is used to limit the overall time an ONU can sojourn in state KN2. The recommended initial value of TK5 is 20 ms.

Figure 15-5 shows a graphic representation of the states of the ONU.

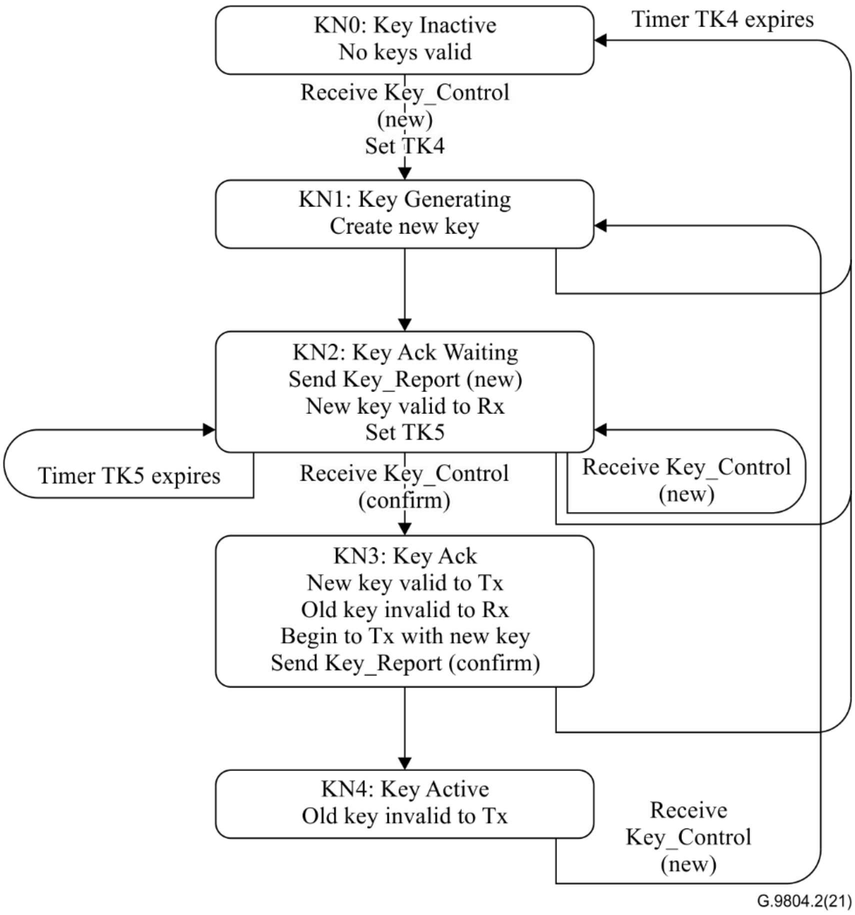


Figure 15-5 – ONU key exchange state diagram

15.5.4 Downstream multicast encryption

The key exchange process is initiated by the OLT CT. The OLT CT selects the key index to be changed. The OLT CT takes this key index out of use, to avoid key mismatch during the process of re-keying. The OLT CT generates each broadcast key using a random number generator suitable for cryptographic purposes.

Using OMCI, the OLT CT then writes the key to the broadcast key table attribute (see clause 9.13.11 of [ITU-T G.988]) in the management information base (MIB) of each ONU that is provisioned to receive multicast traffic. The broadcast encryption key is encrypted with the selected BC-ECB algorithm using the KEK. Note that broadcast functions can only be used amongst ONUs are are using the same encryption algorithm.

The OMCI is an acknowledgement-based protocol, so the OLT CT can confirm that the ONU has indeed modified the key attribute in question. Once the OLT CT has confirmed that all relevant ONUs have the new broadcast key, the OLT CT can put the key index back into service.

15.6 Integrity protection and data origin verification for PLOAM

For the PLOAM messaging channel, sender identity verification and protection against forgery is achieved with the use of the 8-byte message integrity check (MIC) field of the PLOAM message format.

15.6.1 Cryptographic method

The MIC field of the PLOAM message format is constructed using the cipher-based message authentication code (CMAC) algorithm specified in [NIST SP800-38B] with the 128-bit Advanced encryption standard (AES-128) encryption algorithm [NIST FIPS-197] as the underlying block cipher (see Figure 15-6). Note that AES-128 is always used no matter what the cipher selection is. This is done so that the PLOAM-MIC can always be calculated no matter what state the cipher selection is, and to enable broadcast PLOAM transmissions.

The parameters and the notation for invocation of the AES-CMAC function are described in clause 15.3.1.

15.6.2 MIC calculation

Given the 40 bytes of the PLOAM message content and the PLOAM integrity key PLOAM_IK, the sender and the receiver can calculate the MIC field as follows:

$$\text{PLOAM-MIC} = \text{AES-CMAC}(\text{PLOAM\_IK}, C_{\text{dir}} \,|\, \text{PLOAM\_CONTENT}, 64) \qquad (15\text{-}7)$$

Where C_{dir} is the direction code: C_{dir} = 0x01 for downstream and C_{dir} = 0x02 for upstream, and *PLOAM_CONTENT* denotes octets 1 to 40 of the PLOAM message.

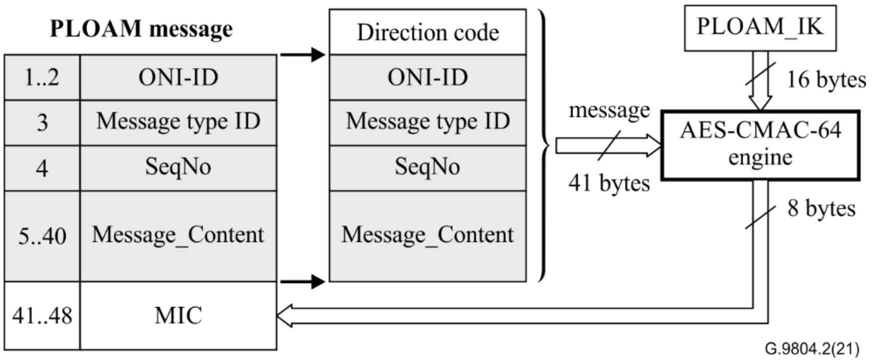


Figure 15-6 – PLOAM integrity protection

15.7 Integrity protection and data origin verification for OMCI

For the OMCI traffic, the sender identity verification and protection against forgery is achieved with the use of the 4-byte message integrity check (MIC) field of the OMCI message format.

15.7.1 Cryptographic method

The MIC field of the OMCI message format is constructed using the cipher-based message authentication code (CMAC) algorithm specified in [NIST SP800-38B] with the selected cipher. The default cipher is the 128-bit advanced encryption standard (AES-128) encryption algorithm [NIST FIPS-197] (see Figure 15-7). Upon activation, the default cipher is used. When the cipher selection is changed, the new cipher is used.

The parameters and the notation for invocation of the BC-CMAC function are described in clause 15.3.1.

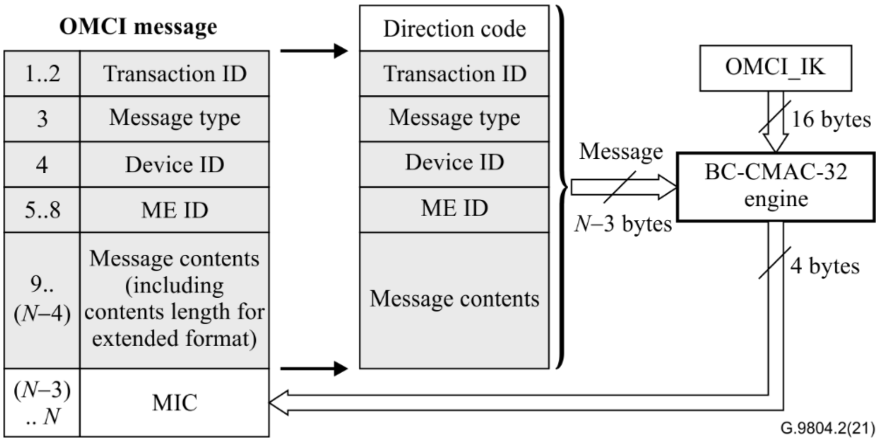


Figure 15-7 – OMCI integrity protection

15.7.2 MIC calculation

Given the content of the OMCI message and the OMCI integrity key OMCI_IK, the sender and the receiver can calculate the MIC field as follows:

$$\text{OMCI-MIC} = \text{BC-CMAC}(\text{OMCI\_IK}, (C_{dir} \mid \text{OMCI\_CONTENT}), 32) \quad (15\text{-}8)$$

Where C_{dir} is the direction code: C_{dir} = 0x01 for downstream and C_{dir} = 0x02 for upstream, and OMCI_CONTENT refers to the OMCI message except the last four bytes.

15.8 Integrity and data origin verification key switching

15.8.1 Use of the default key

At the start of ONU activation, the PLOAM integrity key for the given ONU is set to the default value of $(0x55)_{16}$, which is used for PLOAM message exchange while no MSK is available. Once the ONU communicates its Registration_ID to the OLT CT, the basic MSK is established and all the derivative shared keys are obtained. The OMCI integrity key does not require an explicit default, as no OMCI exchange takes place prior to MSK establishment and no broadcast OMCC is supported.

The downstream broadcast PLOAM messages, as well as certain types of the upstream and downstream unicast PLOAM messages (such as the Serial_Number_ONU PLOAM message, the Deactivate_ONU-ID PLOAM message, the Request_Registration and Registration PLOAM messages) are always protected by a MIC that is generated with the default PLOAM integrity key. These messages, therefore, can be successfully transmitted even if the OLT CT and ONU have not established or no longer agree on the dynamically derived keys. See PLOAM message formats for individual PLOAM message types in clauses 11.3.3 and 11.3.4 for the details of the default PLOAM integrity key applicability.

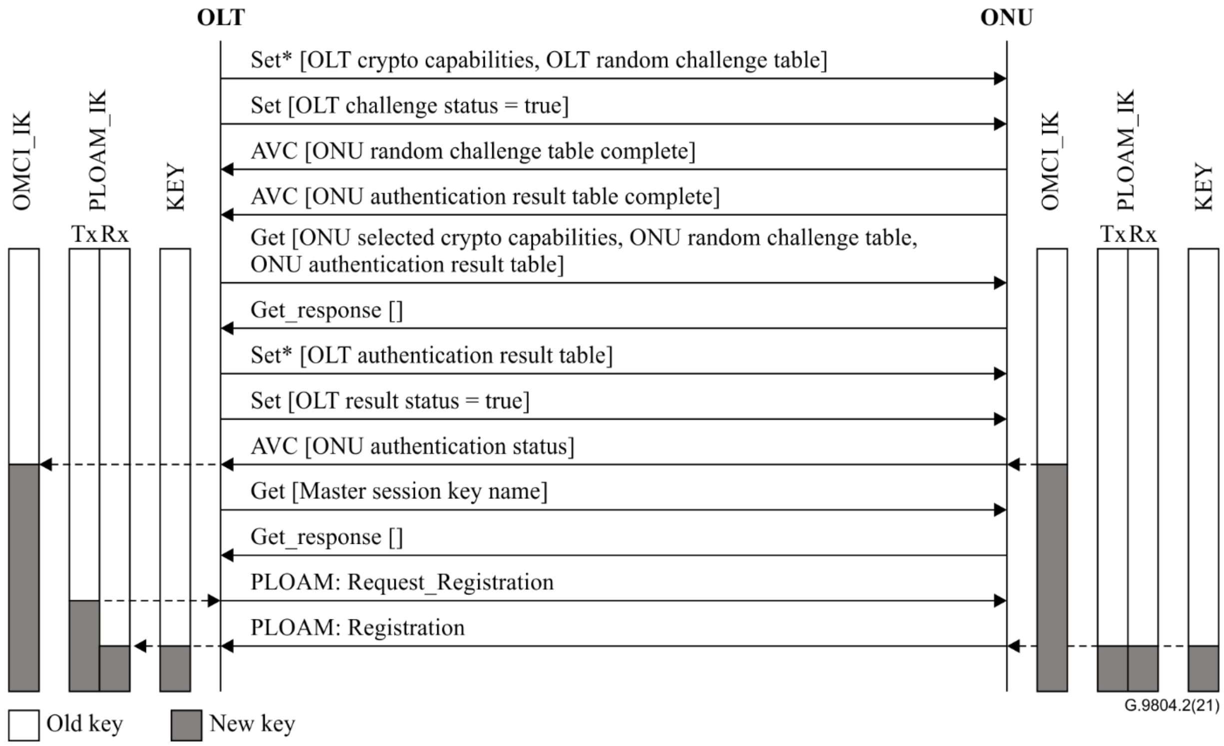
15.8.2 Key switching for OMCI-based secure mutual authentication

The following description refers to the Enhanced security control attributes and procedures specified in clause 9.13.11 of [ITU-T G.988].

The authentication is implemented as a three-step symmetric-key-based challenge-response procedure in the OMCC followed by a PLOAM handshake in the form of Registration_ID exchange.

The OLT CT initiates the OMCI-based authentication at its discretion by writing the OLT CT random challenge table attribute. From this point to the completion of the authentication procedure, the OLT CT refrains from sending to the ONU any OMCI messages unrelated to authentication.

The ONU generates a random challenge of its own, computes the response to the OLT CT challenge, and initiates the secure MSK and derived shared key calculation procedure. Once computed, the secure keys are stored for future use.



NOTE 1 – Set* indicates multiple set operations as needed to fill the table.
NOTE 2 – Unless explicitly specified otherwise, the messages are exchanged over the OMCC.

Figure 15-8 – OMCI-based secure mutual authentication procedure

Upon receipt of the ONU's response to OLT CT's random challenge along with the ONU random challenge table (see Figure 15-8), the OLT CT unilaterally verifies the ONU's authentication status. If the unidirectional ONU-to-OLT authentication fails, further execution of the authentication procedure is aborted. If the unidirectional ONU-to-OLT authentication succeeds, the OLT CT calculates the MSK and the derivative shared keys, storing them for future use. Once the key calculation is completed, the OLT CT proceeds with execution of the authentication procedure by writing the OLT CT authentication result table and OLT CT result status to the ONU.

Upon receipt of the OLT CT's response, the ONU verifies the OLT CT's authentication status and fills in the ONU authentication state attribute. The ONU uses the next available default Alloc-ID grant opportunity to transmit an attribute value change (AVC) on the ONU authentication state attribute. If the unidirectional OLT-to-ONU authentication has failed, a message integrity check (MIC) on the AVC message is generated using the previously active OMCI_IK. If the unidirectional OLT-to-ONU authentication has succeeded (and thus the mutual authentication has succeeded as well), the MIC field on the AVC message is generated with the new OMCI_IK. The new OMCI_IK is committed active at the ONU.

When the OLT CT receives the AVC on the ONU authentication state from the ONU, it checks whether the MIC field has been generated using the old OMCI_IK or the new OMCI_IK. If the old OMCI_IK was used by the ONU, the OLT CT discards the previously calculated key material. If the new OMCI_IK was used by the ONU, the OLT CT commits the new OMCI_IK as active. The OLT CT then initiates a PLOAM handshake by generating a downstream Request_Registration PLOAM message to the ONU. The purpose of the handshake is to delineate the activation of the secure shared keys in case of authentication success, or to obtain the registration-based MSK and derived shared keys in case of authentication failure. The Request_Registration PLOAM message is protected, by definition, using the default PLOAM_IK. Upon transmission of the Request_Registration message, the OLT CT commits the new PLOAM_IK as active on transmit.

Once the ONU receives the downstream Request_Registration PLOAM message, it generates an upstream Registration PLOAM message, which is protected, by definition, using the default PLOAM_IK. Upon transmission of the Registration message, the ONU commits the new PLOAM_IK and KEK as active.

Once the OLT CT receives the upstream Registration PLOAM message from the ONU, it commits the PLOAM_IK and KEK as active on receive, thus completing the key switching procedure.

15.8.3 Key switching for IEEE 802.1x-based authentication

Once the IEEE 802.1x-based mutual authentication or re-authentication process has completed, the OLT CT and the authenticated ONU have a 200 ms grace interval to compute the new set of derived shared keys. Within this interval, a sender should either remain silent or continue to use the old integrity key and switch to the new one as soon as it detects the new key in the received message, or at the end of the grace interval, at the latest. While the new key is being computed, a receiver continues checking the received messages with the old key. When the new key becomes available, the receiver should start checking messages with both old and new keys and switch to using the new key only once the new key check is successful, or at the end of the grace interval, at the latest.

15.8.4 MIC failure considerations

If MIC failure is caused by random transmission errors, then it is likely a rare event that can be correlated with the observed bit error ratio (BER) level. A persistent MIC failure, on the other hand, is likely caused by an integrity key mismatch at the transmitter and receiver and may indicate either a security threat or a malfunction of the authentication and key generation procedure. In case of persistent message integrity check failure, of which the OLT CT learns either directly (upstream MIC failure) or through the lack of expected management traffic flow from the ONU (downstream MIC failure), the OLT CT recognizes a loss of PLOAM channel ($LOPC_i$) defect or a loss of OMCC ($LOOC_i$) defect for a given ONU and has to select, at its discretion, the appropriate mitigation actions. These mitigation actions may include repeating authentication using the same or an alternative mechanism, blocking upstream and downstream traffic, deactivating or disabling the offending ONU, or executing a rogue ONU diagnostic procedure.

15.9 HSP systems with reduced data encryption strength

Clause 15.9.1 introduces the concept of effective key length. Clause 15.9.2 contains the conditional requirements that are mandatory only for HSP systems with specified effective key lengths less than 128 bits. For an ONU, the effective key length is provisioned using the effective key length attribute (see clause 9.13.11 of [ITU-T G.988]).

15.9.1 Effective key length

The standard key size used for AES data encryption in HSP is 128 bits. Per operator requirements, an HSP system may optionally employ a data encryption system of reduced strength by replacing a part of the key with a well-defined bit pattern. The number of randomly generated bits of the key is referred to as the effective key length.

15.9.2 Data encryption key format

In an HSP system with reduced data encryption strength, the effective key length L_{eff} is a multiple of eight bits, and each network element responsible for data encryption key generation replaces the $(128 – L_{eff})/8$ most significant octets of the 128-bit key with the value 0x55, as shown in Figure 15-9.

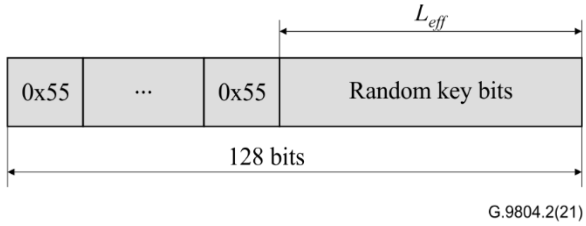


Figure 15-9 – Format of a data encryption key with reduced effective length

In an HSP system with reduced data encryption strength, a network element responsible for the generation of a data encryption key should be able to report the effective key length to the element management system.

16 Power management

For a variety of reasons, it is desirable to reduce the power consumed by an ONU as much as possible:

Over time, the natural evolution of technology tends toward more efficient realizations of given functions, a tendency that is offset, at least to some extent, by increasing levels of functionality and speed.

If there is a way for the ONU to determine that a subscriber interface is idle, it is desirable for the ONU to power down the circuitry associated with that interface, while retaining the capability to detect subscriber activity on that interface. The details vary as a function of the interface type.

The extent of feasible power reduction depends on the acceptable effect on service. The maximum possible savings occurs when a subscriber intentionally switches off an ONU, for example, overnight or during a vacation.

During failures of AC power, some degradation of service is generally acceptable. To conserve backup battery lifetime, it is desirable for the ONU to power down circuitry associated with all interfaces, except those considered to provide essential services. Different operators and customers may have different definitions of essential services, and may wish to prioritize the time when the interfaces are powered down. This feature, which is known as power shedding, is described in clause I.2.7 of [ITU-T G.988].

The preceding techniques for power management are a matter of ONU design and subscriber and operator practice, and are beyond the scope of this Recommendation.

16.1 Power management configuration and signalling

The OLT CT uses OMCI to discover the ONU's power management capabilities and to configure its power management attributes. To control the power management behaviour of a given ONU, the ONU and the OLT CT maintain a pair of power management state machines. The ONU state machine and the corresponding OLT CT state machine operate in partial state alignment. The primary signalling mechanism used to coordinate the ONU and OLT CT state machines is based on the PLOAM messages. The output PLOAM messages are generated and queued for transmission at the time of state transitions. The states of both ONU and OLT CT state machines can be classified into two mutually exclusive subsets: the full power states and the low power states. Only the state transitions between the full power and low power state subsets generate an output PLOAM message. If the sojourn in the target state of a transition is controlled by a timer, the timer is not started until the actual transmission of the message. As a secondary signalling mechanism used to speed up or wake up a sleeping ONU, the forced wake-up indication bit is carried within a BWmap allocation structure.

16.2 Power management parameter definitions

Table 16-1 defines the essential intervals, timers and counters. Parameters known to both ONU and OLT CT are exchanged using OMCI [ITU-T G.988]. Parameters local to the ONU or the OLT CT are defined only for use in the description below.

Table 16-1 – Power management parameters

Parameter	Description	Defined by	Known to
Ilowpower	Ilowpower is the maximum time the ONU spends in its LowPower state, as a count of 125 microsecond frames. Local wake-up indications (LWIs) or remote events, if detected, state may truncate the ONU's sojourn in these states.	OLT CT	ONU, OLT CT
Tlowpower	Local timer at ONU. Upon entry to the LowPower state, the ONU initializes Tlowpower to a value equal to or less than Ilowpower. Secondary internal timers may be required to guarantee that the ONU will be fully operational when it enters the Aware state after an interval not to exceed Ilowpower.	ONU	ONU
Iaware	Iaware is the minimum time the ONU spends in its Aware state before transitioning to the LowPower state, as a count of 125 microsecond frames. During the Iaware interval, local or remote events may independently cause the ONU to enter the ActiveHeld state rather than returning to the Low Power state.	OLT CT	ONU, OLT CT
Taware	Local timer at ONU, initialized to a value equal to or greater than Iaware once downstream synchronization is obtained upon entry to the Aware state. Taware controls the dwell time in the Aware state before the ONU re-enters the LowPower state.	ONU	ONU
Itransinit	The worst-case transceiver initialization time: The time required for the ONU to gain full functionality when leaving the LowPower state, measured in units of 125 μs PHY frames, and known by design. The value of zero indicates that the sleeping ONU can respond to a bandwidth grant without delay.	ONU	ONU, OLT CT
Irxoff	Irxoff is the maximum time the OLT CT can afford to wait from the moment it decides to wake up an ONU in the LowPower state until the ONU is fully operational, specified as a count of 125 microsecond frames. The ONU timer Trxoff and the OLT CT timer Talerted are initialized based on Irxoff,	OLT CT	ONU, OLT CT
Trxoff	Local timer at ONU. The ONU uses this timer in the LowPower state while checking the downstream signal for the remote wake-up indications to ensure that the time between two consecutive checks does not exceed the provisioned Irxoff interval.	ONU	ONU

Table 16-1 – Power management parameters

Parameter	Description	Defined by	Known to
Talerted	Local timer to bound the time that the OLT CT state machine remains in an alerted state before entering the AwakeForced state. Talerted should be initialized to at least Itroff + Itransinit + round-trip delay + tolerances for Rx synchronization, bandwidth grant irregularities, and processing time.	OLT CT	OLT CT
Ter_i	Local handshake timer at the OLT CT that defines the latest instant at which an upstream burst is expected from ONU_i when it is in the LowPower state. The OLT CT reinitializes and starts this timer when the OLT CT 's state machine for the given ONU transition into the LowPowerWatch state and each time an upstream burst is received from the ONU while in that state. If Ter_i expires, the OLT CT declares a handshake violation and attempts to force the ONU awake. To determine the initial value of Ter_i, the OLT CT is responsible to consider the provisioned Ilowpower interval and any possible effects of transceiver initialization, synchronization and irregularities in the bandwidth grant cycle.	OLT CT	OLT CT
Ihold	Minimum sojourn in the ActiveHeld state.	OLT CT	ONU, OLT CT
Thold	Local timer at the ONU that is initialized to Ihold upon transmission of SR(Awake) after entry into ActiveHeld state and that enforces the minimum sojourn in the ActiveHeld state.	ONU	ONU

16.3 Power management state machine specifications

The power management behaviour of a given ONU is controlled by a pair of state machines residing at the OLT CT and the ONU. While the state nomenclature of the OLT CT machine is similar to that of the ONU machine, the two state machines operate in just partial state alignment. The lock-step state tracking is not an objective of the protocol.

16.3.1 ONU state machine

The ONU power management states along with their corresponding semantic description are listed in Table 16-2. The set of input events is represented in Table 16-3. The state transition diagram is illustrated in Figure 16-1. The normative specification of the state transitions and outputs is given in Table 16-4.

Table 16-2 – ONU power management states

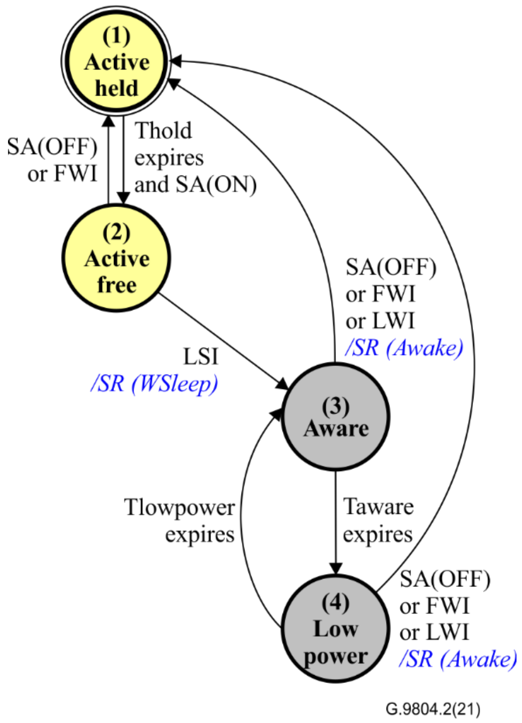
State	Semantics
(1) ActiveHeld	The ONU is fully responsive, forwarding downstream traffic and responding to all bandwidth allocations. Power management state transitions do not occur. The minimum sojourn in this state is enforced by the Thold timer. Upon entrance to this state, the ONU sends a Sleep_Request (Awake) PLOAM message. On the state diagrams, this is abbreviated as SR(Awake).

Table 16-2 – ONU power management states

State	Semantics
(2) ActiveFree	The ONU is fully responsive, forwarding downstream traffic and responding to all bandwidth allocations. Power management state transition requests are a local decision.
(3) Aware	Both ONU receiver and transmitter remain on. This state persists for a specified duration Iaware if not truncated by the arrival of a local stimulus LWI or receipt of SA(OFF) from the OLT CT. The ONU forwards downstream traffic and responds to all grant allocations. It is the responsibility of the OLT CT to transmit bandwidth allocations containing the PLOAMu flag with frequency sufficient to ensure that an aware ONU sees at least one.
(4) LowPower	The ONU transmitter is off. The ONU periodically checks the downstream signal for remote wake-up indications. When the downstream signal is checked, the ONU does not respond to grant allocations and does not forward downstream traffic. This state persists for a specified duration Ilowpower if not truncated by the arrival of a local stimulus LWI or receipt of SA(OFF) or FWI from the OLT CT. Before exiting this state, the ONU ensures that it is fully powered up and capable of responding to both upstream and downstream traffic and control.

Table 16-3 – ONU state machine inputs

Input categories	Input	Semantics
PLOAM events	Sleep_Allow(ON)	The OLT CT grants permission to the ONU to exercise watchful sleep management mode.
	Sleep_Allow(OFF)	The OLT CT withholds consent to exercise a power management mode.
Bit-indication event	Forced wake-up indication (FWI)	Transmitting FWI as a flag of an allocation structure, the OLT CT requires immediate ONU wake-up and its transition to the ActiveHeld state.
Timer events	Thold expiration	The event applies in the ActiveHeld state, controlling the minimum sojourn in that state.
	Taware expiration	The event applies in the Aware state, controlling the sojourn in that state.
	Tlowpower expiration	The event applies in the LowPower state, controlling the sojourn in that state.
Local events	Local sleep indication (LSI)	The ONU has no local reason to remain at full power and is willing to exercise the watchful sleep power management mode.
	Local wake-up indication (LWI)	A local stimulus prevents the ONU from exercising any power management mode.
NOTE – The LSI and LWI events are conceptually derived from the ONU's binary stimulus status level (Awake/Sleep) and correspond to the events of the level change or, in case of ActiveFree state, to the sampled value at the time of the transition. The specific criteria for the local stimulus definition remain out of scope of this Recommendation.		



NOTE – The vertices on the state diagram graph can be qualified as either "tense" or "relaxed" forming the yellow and grey subgraphs, respectively. As a rule, an output PLOAM message is generated only on a state transition that crosses the subgraph boundary.

Figure 16-1 – ONU state transition diagram (initial state circled)

Table 16-4 – ONU state transition and output table

Inputs	**ONU power management states**			
	(1) ActiveHeld	**(2) ActiveFree**	**(3) Aware**	**(4) LowPower**
FWI	*	→ (1)	→ (1) /SR(Awake)	→ (1) /SR(Awake)
SA (OFF)	*	→ (1)	→ (1) /SR(Awake)	→ (1) /SR(Awake)
SA (ON)	→ (2) Upon Thold expiration (Note)	*	*	*
LWI	*	*	→ (1) /SR(Awake)	→ (1) /SR(Awake)
LSI		→ (3) /SR(WSleep)	*	*
Tlowpower expiration				→ (3)

Table 16-4 – ONU state transition and output table

Inputs	ONU power management states			
	(1) ActiveHeld	**(2) ActiveFree**	**(3) Aware**	**(4) LowPower**
Taware expiration			→ (4)	

* Indicates a self-transition.

A shaded cell means that the input is not applicable in the given state.

NOTE – An ONU remains in the ActiveHeld state for at least Ihold upon entry into that state regardless of the SA message parameter value indicated by the OLT CT. The minimum sojourn in the ActiveHeld state is controlled by timer Thold that is initiated to Ihold upon ONU's entry into the ActiveHeld state. When Thold expires, the ONU executes a transition into to the ActiveFree state if the latched value of SA message parameter is ON or as soon as SA (ON) message is received.

16.3.2 OLT CT state machine

The OLT CT power management states along with their corresponding semantic description are listed in Table 16-5. The set of input events is represented in Table 16-6. The state transition diagram is illustrated in Figure 16-2. The normative specification of the state transitions and outputs is given in Table 16-7.

Table 16-5 – OLT CT power management states

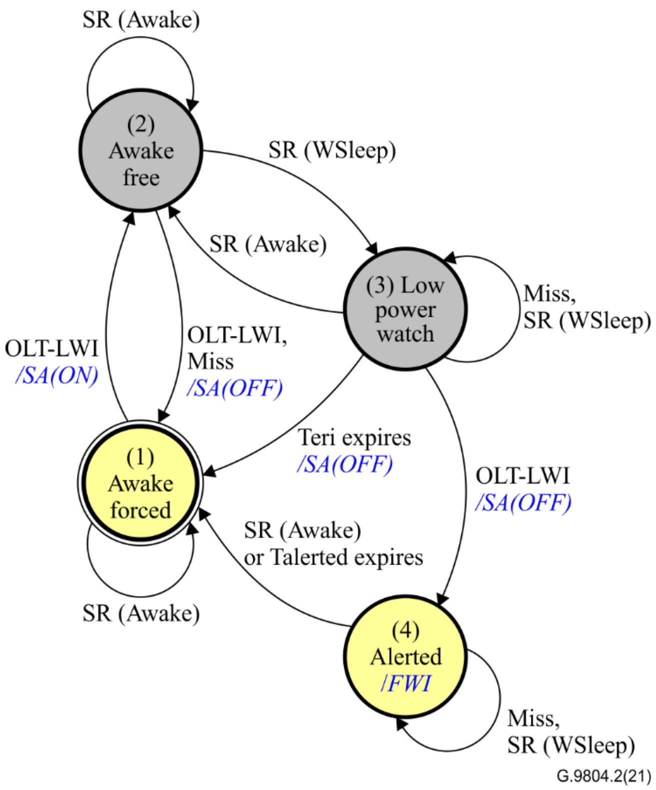
State	Semantics
(1) AwakeForced	The OLT CT provides normal allocations to ONU_i, forwards downstream traffic, and expects a response to every bandwidth grant. The OLT CT declares the LOB_i defect on detection of the specified number of missed allocations. On transition into this state, the OLT CT sends a Sleep_Allow (OFF) PLOAM message, thus revoking its permission to the ONU to enter the LowPower state.
(2) AwakeFree	The OLT CT provides normal allocations to the ONU, forwards downstream traffic, and is ready to accept a power management transition indication from the ONU. On transition into this state, the OLT CT sends a Sleep_Allow (ON) PLOAM message, thus granting the ONU a permission to enter the LowPower state at its own discretion. The OLT CT expects a response to every bandwidth grant, and in case of missed allocation transitions to the AwakeForced state, where LOB_i condition can be eventually declared. There are two stable state combinations involving the AwakeFree state of the OLT CT state machine: the ONU state machine can be either in the ActiveFree state or in the ActiveHeld state.

Table 16-5 – OLT CT power management states

State	Semantics
(3) LowPowerWatch	The OLT CT supports the ONU in a low power state. The OLT CT provides normal allocations to the ONU but expects only intermittent responses from the ONU to bandwidth grants, as defined by various timers. The OLT CT may either discard or buffer the downstream traffic. If timer Ter_i expires before the OLT CT receives a burst from ONU_i, the OLT CT recognizes a handshake violation and goes to the AwakeForced state.
(4) Alerted	The OLT CT attempts to wake up the ONU. Having sent Sleep_Allow (OFF) message on transition to the state, the OLT CT sets the FWI bit in every allocation to the ONU along with the PLOAMu flag. The OLT CT discards or buffers downstream traffic for the ONU, just as it did during the immediately preceding LowPowerWatch state. The OLT CT goes to the AwakeForced state if it receives a burst from the ONU that includes a Sleep_Request (Awake) PLOAM message or if timer Talerted expires.

Table 16-6 – OLT CT state machine inputs

Input categories	Input	Semantics
PLOAM events	Sleep_Request (WSleep)	The ONU informs the OLT CT of its intent to exercise the watchful sleep power management mode.
	Sleep_Request (Awake)	The ONU informs the OLT CT of its intent to remain at full power.
Timer events	Ter_i expiration	The event occurs only in the LowPowerWatch state indicating the violation by the ONU of the provisioned low power timing parameters.
	Talerted expiration	The event occurs only in Alerted state indicating the ONU's failure to wake-up upon OLT CT's demand.
Local events	Local wake-up indication, OLT-LWI	Local wake-up indication and its inverse indicate, respectively, the presence and the absence of a local stimulus to maintain the ONU at full power.
NOTE – The OLT-LWI event and its inverse are conceptually derived from the OLT CT's binary stimulus status level and correspond to the stimulus level change. The specific criteria for the local stimulus definition remain out of scope of this Recommendation.		



NOTE – The vertices on the state diagram graph can be qualified as either "tense" or "relaxed" forming the yellow and grey subgraphs, respectively. As a rule, an output PLOAM message is generated only on a state transition that crosses the subgraph boundary.

Figure 16-2 – OLT CT state transition diagram (initial state circled)

Table 16-7 – OLT CT state transition and output table

Inputs	**OLT CT power management states**			
	(1) AwakeForced	**(2) AwakeFree**	**(3) LowPowerWatch**	**(4) Alerted / FWI**
SR (Awake)	*	*	→ (2)	→ (1)
SR (WSleep)	* /SA(OFF) (Note 1)	→ (3)	*	*
Allocation miss	*	→ (1) /SA(OFF)	*	*
OLT-LWI ON	*	→ (1) /SA(OFF)	→ (4) /SA(OFF)	*

Table 16-7 – OLT CT state transition and output table

Inputs	OLT CT power management states			
	(1) AwakeForced	**(2) AwakeFree**	**(3) LowPowerWatch**	**(4) Alerted / FWI**
OLT-LWI OFF	→ (2) /SA(ON)	*	*	* (Note 2)
Talerted exp.				→ (1)
Ter_i exp.			→ (1) /SA(OFF)	
NOTE 1 – An exception from the subgraph rule; an output may help to stabilize the state machine in case the condition is caused by a lost SA(OFF) message. The output is not shown on the state transition diagram. NOTE 2 – This is a situation when the OLT CT initiates a wake-up, but the OLT-LWI is cleared before the ONU is awoken. In this case, the OLT CT, instead of cancelling the wake-up process and attempting to immediately revert to a low power state, insists on waking the ONU up with the intent to re-enter a low power state via states AwakeForced and AwakeFree.				

16.4 Management transactions in the LowPower state

The ONU can receive and act on downstream management traffic at any of the three channels described in clause 6.4, except when it is in its LowPower state and has its receiver switched off. The OLT CT is responsible for understanding when the ONU can be expected to receive downstream management traffic, or to deal with the possibility that the ONU does not receive such traffic.

If the ONU receives embedded OAM commands such as DBRu or PLOAMu when it cannot respond immediately, i.e., when it is in its LowPower state, it ignores the commands. It is the OLT CT's responsibility to allow for extra response delays if it sends PLOAM or OMCI commands to an ONU that may be incapable of responding within the normal time (for example, within 750 µs for a PLOAM command).

It is prudent for the OLT CT to force the ONU awake before conducting management transactions.

The OLT CT is permitted to send unidirectional management transmissions at any time, including Profile, Deactivate_ONU-ID, Disable_Serial_Number, and Sleep_Allow PLOAM messages. The OLT CT must be prepared for the possibility that a sleeping ONU does not receive the transmission.

For the purposes of this clause, an ONU sleeps only when it is in O5 state. When the OLT CT understands that the ONU is not in O5 state, for example, because the ONU is only newly discovered or has not yet registered, the normal ranging and assignment transactions occur without regard to the power saving states.

16.5 Power saving by channel selection

The ONU power consumption may change in different TWDM channels, given ONU's own component characteristics. The OLT can collect ONU power consumption information via PLOAM messages Power_Consumption_Report, and then instruct the ONU to tune to the wavelength channel with lower power consumption.

17 TWDM channel management

This clause contains the procedural specification of the following functions in TWDM:

– Profile announcement

– ONU calibration

– ONU wavelength channel handover

– ONU wavelength channel locking

– ONU wavelength channel bonding

In addition, the wavelength channel protection is addressed within clause 18, and the rogue ONU detection and mitigation are addressed in clause 19.

The related material can be found elsewhere in the Recommendation: the PLOAM channel specification (clause 11), the specification of the ONU activation cycle state machine (clause 12). The description of the ICTP primitives can be found in Appendix VI.

17.1 TWDM profile announcement

The profile announcement in TWDM is transmitted in a form of a series of unacknowledged broadcast PLOAM messages on each downstream wavelength channel and consists of:

– a single System_Profile PLOAM message;

– a set of Channel_Profile PLOAM messages, one per deployed channel pair (up to eight);

– a set of Burst_Profile PLOAM messages, one per burst profile referenced by the BWmaps distributed over the given downstream wavelength channel.

The complete set of profiles is distributed periodically with the period TminProfile, which can be set between 1 and 5 seconds.

A system profile consists of the SYS ID, system profile version number, and the TWDM system descriptor (see clause 11.3.3.13).

A channel profile consists of a block of common parameter (that is, a Channel profile identifier, downstream and upstream void indicators, *this* channel indicator, channel profile version number, PON-ID), a downstream wavelength channel descriptor, and an upstream wavelength channel descriptor (see clause 11.3.3.14).

A Channel_Profile message can include parameters for both of a downstream wavelength channel and an upstream wavelength channel, however both of the relevant OLT channel terminations (upstream and downstream) control the profile parameters and are not necessarily bound together as a channel pair.

In the simplest case, each Channel_Profile message specifies a static one-to-one association between the upstream and downstream wavelength channels: an ONU which is listening to the given downstream wavelength channel responds in the given upstream wavelength channel. In the most general case, however, the association between the downstream wavelength channels and upstream wavelength channels is flexible and dynamic, including the possibility to support one-to-many and many-to-one channel association options. In that case, a Channel_Profile message just establishes a naming convention and may have either its downstream descriptor or its upstream descriptor void.

The flexible association between the downstream and upstream wavelength channels is supported by the default response channel attribute of a downstream channel descriptor in the Channel_Profile message, and by separate specification of the target downstream and upstream wavelength channels in the Tuning_Control PLOAM message. Since the profile announcement format and composition is the same for static and flexible association, no explicit indication is required.

17.1.1 TWDM system and channel descriptors

A system descriptor is a collection of TWDM system parameters and their specified values.

Table 17-1 – System descriptor content

Parameter	Description	Note
Channel count	The number of TWDM channels with distinct Channel Profile identifiers that exist in the system. Note 1 – Each channel is counted once, regardless of the number of its Type B peer CTs. Note 2 – If a TWDM channel is supported in an HSP system, but is temporarily not operational in the upstream and/or downstream directions, it is included into the TWDM channel count, and the corresponding Channel_Profile PLOAM message announces its upstream and/or downstream wavelength channel descriptors as void.	
Upstream wavelength channel spacing	The upstream wavelength channel spacing serving as an ONU Tx scaling factor (i.e., ONU Tx parameters, such as spectral width and MSE, are required to be consistent with this specification). Note – Channel spacing is a system parameter characterizing the grid to which the system is designed, rather than how the wavelength channels are deployed.	
MSE	Maximum spectral excursion represented as an unsigned integer indicating the value in units of 1 GHz.	
FSR	If a cyclic WM is used in the upstream, Free spectral range (FSR) is represented as an unsigned integer indicating the value in units of 0.1 GHz. If a cyclic WM is not used, the field contains the value 0x0000.	
Upstream operating wavelength band	Upstream wavelength band option (per the applicable PMD Recommendations).	Options: wide, reduced, or narrow.
Calibration accuracy	The minimum calibration accuracy that an ONU should meet in order to proceed with activation.	

Table 17-1 – System descriptor content

Parameter	Description	Note
Loose calibration bound	Run-time specification of the spectral excursion bound below which a TWDM ONU can be considered as loosely calibrated. The value of this parameter depends on the WM characteristics which are up to the implementer. Therefore, it is not for standards to determine how loose the ONU wavelength calibration can be to avoid interference with other channels. This is conveyed to the ONU by the OLT.	

A wavelength channel descriptor is a collection of parameters and their specified values pertaining to the downstream and upstream wavelength channels. A Channel_Profile PLOAM message carries the TWDM parameter set.

Table 17-2 – Channel profile elements

Parameter	Description	Note
Channel profile identifier	Channel profile identification that must be unique for each TWDM channel that exists in the system. The total number of channel profiles is set by the Channel count of the system descriptor (see Table 17-1).	4 bit field
This channel indicator	The flag is set if and only if the profile pertains to the channel in which the profile is transmitted.	
DS void indicator	Downstream wavelength channel descriptor portion of the profile is void.	
US void indicator	Upstream wavelength channel descriptor portion of the profile is void.	
PON-ID	A 32-bit static value which is carried in the OC structure and uniquely identifies a TWDM channel termination (CT) entity within a domain (see clause10.1.1.3).	Consists of 28 bit administrative label and 4-bit DWLCH ID.
Downstream frequency	The frequency specification of the downstream wavelength channel.	Specified as an offset with respect to a well-defined wavelength reference
Downstream line rate	The specification of the data rates supported by the OLT in the given wavelength channel in the downstream direction. In a profile of *this* channel this parameter is included for reference only, as the ONU already knows the value when receiving the message.	An indicator of the downstream nominal line rate
Downstream FEC indication	Downstream FEC ON/OFF indicator. In a profile of *this* channel this parameter is included for reference only, as the ONU already knows the value when receiving the message.	
Downstream line coding	Downstream line code specification. In a profile of *this* channel this parameter is included for reference only, as the ONU already knows the value when receiving the message.	

Table 17-2 – Channel profile elements

Parameter	Description	Note
Channel partition index	An index of the operator-specified channel subset in TWDM. During operation, the ONUs can be re-tuned between the channels within a channel partition, but not across the boundaries of the channel partition.	
Default response channel	The UWLCH ID of the upstream wavelength channel in which the ONU is required to transmit when listening and obtaining the Bandwidth Map from *this* downstream wavelength channel.	
UWLCH ID	Assigned upstream wavelength channel identifier.	4 bit field
Upstream frequency	The frequency specification of the upstream wavelength channel: a single nominal central frequency, or a root frequency of a cyclic set of nominal central frequencies forming an upstream wavelength channel.	
Optical link type	Upstream optical link type defined in the applicable PMD Recommendations	
Upstream line rate	The specification of the data rates supported by the OLT in the given wavelength channel in the upstream direction.	Specified as a bitmap indicating supported line rates
Default ONU attenuation	The initial attenuation level in the course of ONU activated power levelling.	
Response threshold	The limit on the number of PLOAM messages the ONU can transmit at non-zero attenuation level while attempting to establish communication with OLT CT.	

17.1.2 Profile parameter learning by ONU

An OLT CT transmits each component of the profile announcement at regular intervals, frequently enough to ensure proper operation of the ONUs. The transmission frequencies of the individual profile announcement components should be reasonably consistent; however, strict periodicity and phase alignment are not required.

In order to be able to activate on the TWDM HSP system, an ONU should receive and process at least: the System_Profile PLOAM message, a Channel_Profile PLOAM messages for the downstream wavelength channel and the upstream wavelength channel the ONU intends to operate on, a Burst_Profile PLOAM message for each burst profile specified in the bandwidth allocations the ONU intends to respond to.

The ONU begins learning the system, channel, and burst profile parameters once it reaches state O1.2 of the ONU activation cycle state machine, and continues learning the profile parameters through the activation cycle, as long as it stays synchronized to the downstream PHY frames.

The ONU discard the learned burst profile parameters each time it completes an activation cycle (i.e., enters state O1.1). The ONU retains the system and channel profile parameters through the completion of the activation cycle, unless it enters state O1.1 from state O7, that is, recovers from Emergency Stop state (O7). In the latter case, the system and channel profile parameters are discarded along with the burst profile parameters.

17.2 TWDM ONU calibration

To operate in a TWDM HSP system, an ONU must maintain calibration, that is, be able to accurately tune, when instructed, to specific operating downstream and upstream wavelength channels. Achieving calibration amounts to building and maintaining the transmitter and receiver calibration record, which establishes association between the specified parameters of the available wavelength channels, on the one hand, and the corresponding values of the ONU tuning control parameters, on the other hand.

The ONU transceiver calibration can be achieved in advance and/or in service, with appropriate feedback control. The feedback control loop for downstream channel calibration can be closed by an ONU autonomously and, therefore, requires just minimal ComTC layer support.

With respect to the upstream wavelength channel calibration, for which the feedback control loop necessarily involves the OLT CT, the ComTC layer specification provides a toolbox to accommodate the TWDM ONUs with wide range of calibration properties. These include ONUs calibrated in advance with autonomously stabilized transmission wavelength, ONUs calibrated in advance with externally adjustable transmission wavelength, as well as ONUs with no advance calibration.

The OLT CTs provide the nominal wavelength information for each downstream and upstream wavelength channel as a part of the channel profile. If the downstream operating wavelength is systematically different from the nominal wavelength and the shift is known to the OLT, this information is included into the channel profile as well.

17.2.1 In-service downstream wavelength channel calibration

An ONU, which has not been calibrated in advance, may perform downstream wavelength channel calibration on its own discretion in state O1, upon activation (reactivation), for the wavelength channels available at the time, and in state O8, while executing a Tuning_Control command, for previously uncalibrated wavelength channels. The ONU scans the receiver tuning range, acquiring synchronization to the downstream optical signal where such signal is available, obtaining the wavelength channel parameters from the Channel_Profile announcements, and recording the association between those parameters and the corresponding values of the internal tuning control parameters.

While the ONU receiver is in the stationary wavelength channel state, the ONU (whether calibrated in advance or not) may adjust the calibration for the operating wavelength channel. The calibration adjustment may be achieved, for example, through an autonomous dithering process by adding low amplitude modulation to the internal receiver tuning control parameters and following the optimal quality of the received optical signal.

If the ONU learns from the System_Profile and Channel_Profile announcements that a specific downstream wavelength channel has been taken out of operation, it voids the corresponding calibration record.

17.2.2 In-service upstream wavelength channel calibration

An ONU performs upstream wavelength channel calibration under the OLT CT guidance in O2-3, upon activation (reactivation), for any upstream wavelength channel of OLT's choosing, and in state O9, while executing a Tuning_Control command, for the target upstream wavelength channel.

The ONU makes the best effort to tune its transmitter to the specified operating upstream wavelength channel and responds to the SN grants in state O2-3 or directed PLOAM grants in state O9, adjusting the transmit wavelength and power, if capable of doing so, until it receives a feedback from the OLT CT. Upon receiving the OLT CT feedback, the ONU may adjust its calibration record for the operating upstream wavelength channel (unless it has been fixed in advance) and follows further instructions from the OLT CT. If a timer controlling ONU's sojourn in states O2-3 or O9 expires without the ONU receiving the OLT CT feedback, the ONU performs reactivation.

To assist the OLT CT in arriving at the calibration decision, the ONU reports its calibration record status while responding to the SN grants in states O2-3 or directed PLOAM grants in state O9.

While the ONU transmitter is in the stationary wavelength channel state, and if the ONU supports fine wavelength tuning, the OLT CT may engage the ONU in a closed loop upstream wavelength control through the dithering mechanism (see clause 17.4).

If the ONU learns from the System_Profile and Channel_Profile announcements that a specific upstream wavelength channel has been taken out of operation, it voids the corresponding calibration record.

17.3 TWDM ONU wavelength channel handover

This clause describes a pre-planned ONU handover between two TWDM channels. A pre-planned ONU handover may take place upon ONU activation, during the load balancing operation, in support of the OLT software upgrade, in the course of execution of an OLT power saving, OLT-pay-as-you-grow, rogue ONU mitigation procedure and in other situations.

17.3.1 Causal sequence of ONU handover events

The following description refers to Figure 17-1, which represents a causal sequence of events involved in a successful handover. The ONU activation cycle states are referred to in clause 12. The OLT CT states (Unaware, Expecting, Hosting, Redirecting, and Seeing-Off) are explained in clause 17.3.3. In the figure, the solid slanted arrow represents a data or PLOAM transmission, a dashed arrow – a PLOAM allocation and a horizontal bar – an ICTP interaction. See Appendix VI for ICTP.

1) Initially, the ONU is hosted by the Source OLT CT, and the two NEs exchange data and PLOAM messages as specified elsewhere in this Recommendation.
2) The Source OLT CT and the Target OLT CT execute a transaction over the ICTP resolving that the ONU is to be handed from the Source OLT CT to the Target OLT CT. The transaction is committed with the Source OLT CT receiving the ICTP:Tune-Out indication, and the Target OLT CT receiving the ICTP:Tune-In indication.
3) Upon committing the ONU handover transaction, the Target OLT CT instantiates necessary data structures to support the ONU, begins issuing periodic directed PLOAM grants to the ONU, ensuring that the appropriate guard time is provided, and starts the T_{target} timer which controls the duration of the handover operation from the perspective of the Target OLT CT.
4) Upon committing the ONU handover transaction, the Source OLT CT starts the T_{source} timer, which controls the duration of the handover operation from the perspective of Source OLT CT, and sends a Tuning request to the ONU in the form of a Tuning_Control PLOAM message, specifying the downstream and upstream wavelength channels of the Target TWDM channel, the Scheduled SFC value, that is, the 16 least significant bits of the SFC of the PHY frame when the transceiver tuning is scheduled to commence, and the Rollback support indication.
5) The ONU evaluates the Tuning request and, if it can be accepted, responds with a Tuning acknowledgement in the form of a Tuning_Response(ACK) PLOAM message and starts the preparations for handover. If ONU cannot accept the Tuning request to any reason, for example, the Scheduled SFC being too close to the current PHY frame, it can reject it with a Tuning_Response(NACK) PLOAM message, providing the appropriate response code.
6) After the Source OLT CT receives the Tuning acknowledgement, it may continue issuing the ONU directed PLOAM grants, whether or not the ONU responds, to facilitate ONU rollback in case the handover is not successful.

7) When the Scheduled SFC value matches the 16 least significant bits of the locally maintained SFC copied from the PSBd structure of the downstream PHY frames, the ONU starts tuning its transceiver to the specified downstream and upstream wavelength channels.

8) Once the ONU completes transceiver tuning and acquires downstream synchronization, it starts parsing the BWmap, and responds to the appropriate PLOAM allocations with a Tuning_Response(Complete_u) PLOAM message. (If the ONU fails to tune its transceiver to the target downstream or upstream wavelength channels and the Source OLT CT has offered the Rollback support, the ONU may restore its transceiver to the source downstream and upstream wavelength channels and announce its return to the Source OLT CT by transmitting a Tuning_Response(ROLLBACK) PLOAM message.)

9) When the Target OLT CT receives an indication of the ONU arrival, it may issue a Request_Registration PLOAM message to authenticate the ONU. It completes the handshake with the ONU with the Tuning_Control(Complete_d) PLOAM message and starts the ICTP:confHandover transaction with the Source OLT CT. The ONU re-derives the SK, the OMCI_IK, the PLOAM_IK, and the KEK when the PON-TAG in the downstream Burst_Profile PLOAM message changes.

10) Upon receiving the handover confirmation, the Source OLT CT stops issuing the bandwidth allocations to the ONU, and abandons any data structures associated with it.

11) The Target OLT CT and the ONU engage in operation exchanging data and PLOAM messages as specified elsewhere in this Recommendation.

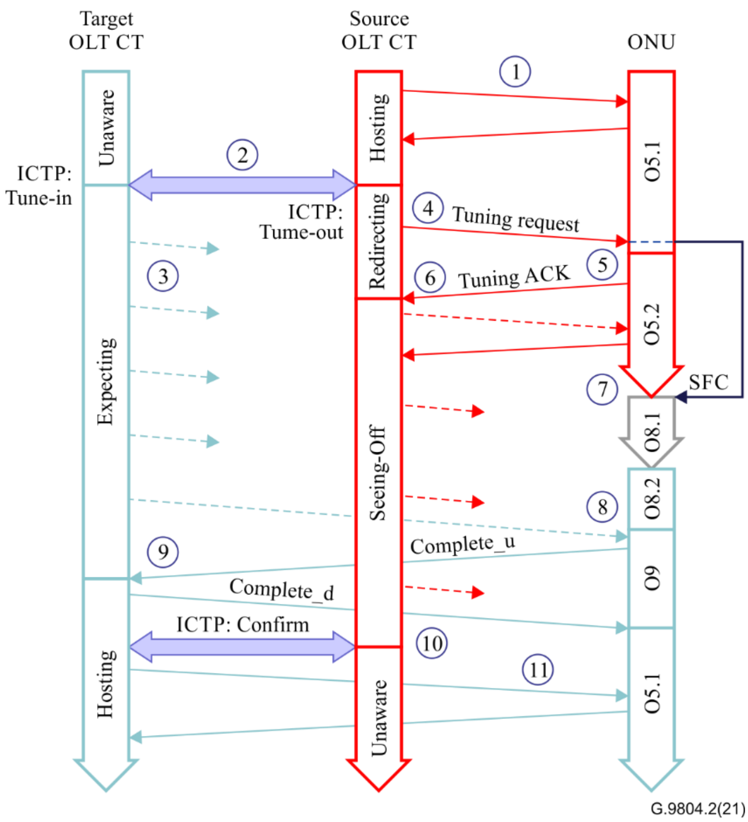


Figure 17-1 – Causal sequence of ONU handover events

17.3.2 ONU wavelength channel handover failure conditions

An ONU which is instructed to execute a handover to a specified target TWDM channel may be unable to do so due to one or more of the failure conditions specified in Table 17-3. The failure conditions are qualified as either internal (INT), stemming from the hardware or software limitation of the ONU itself; downstream inconsistency (DS), based on the evaluation of the target downstream wavelength channel descriptor; or upstream inconsistency (US), based on the evaluation of the target upstream wavelength channel descriptor. These conditions are reported by the ONU in the Tuning_Response PLOAM message with NACK operation code.

Table 17-3 – Failure conditions reported with NACK operation code

No	Group	Code	Condition
1	INT	INT_SFC	The ONU is not ready to start transceiver tuning by Scheduled SFC.
2	DS	DS_ALBL	The Administrative label portion of the specified target downstream PON-ID does not match the learned Administrative label for the DWLCH ID.
3	DS	DS_VOID	The descriptor of the specified target downstream wavelength channel is void.
4	DS	DS_PART	The ONU's non-default channel partition does not match the channel partition of the target downstream wavelength channel.
5	DS	DS_TUNR	The central wavelength of the downstream wavelength channel is outside of the ONU's receiver tuning range.
6	DS	DS_LNRT	The ONU's supported downstream line rate does not match the line rate of the target downstream wavelength channel.
7	DS	DS_LNCD	The ONU's supported downstream line code does not match the line code of the target downstream wavelength channel.
8	US	US_ALBL	The Administrative label portion of the specified target upstream PON-ID does not match the learned Administrative label.
9	US	US_VOID	The descriptor of the specified target upstream wavelength channel is void.
10	US	US_TUNR	All the central wavelengths of the target upstream wavelength channel are outside of ONU's transmitter tuning range.
11	US	US_CLBR	The upstream wavelength channel calibration accuracy is worse than the specified minimum calibration accuracy for activation (Note).
12	US	US_LKTP	The ONU's optical link type is not supported by the target upstream wavelength channel.
13	US	US_LNRT	The ONU's supported upstream line rate does not match the line rate of the target upstream wavelength channel.
14	US	US_LNCD	The ONU's supported upstream line code does not match the line code of the target upstream wavelength channel.
NOTE – This condition prevents the ONU from executing the handover only if it has not been suppressed by the calibration flag of the Tuning_Control message.			

An ONU which has commenced executing the handover to a specified target TWDM channel may be unable to complete the operation due to one or more of the failure conditions specified in Table 17-4. The failure conditions fall into one of three groups: communication (COM) – inability to execute the handshake in the target TWDM channel; downstream consistency (DS) – the information received in the PSBd field of the target downstream wavelength channel frame contradicts the stored wavelength channel descriptors; or upstream consistency (US) – the information obtained via Channel_Profile PLOAM messages in the target downstream wavelength channel contradicts ONU supported parameters. If the ONU executes a rollback to the source TWDM channel, it reports the failure condition or conditions to the OLT in the Tuning_Response PLOAM message with ROLLBACK operation code.

Table 17-4 – Failure conditions reported with ROLLBACK operation code

No	Group	Code	Condition
1	COM	COM_DS	The ONU has failed to obtain DSYNC on the target downstream wavelength channel.
2	DS	DS_ALBL	The Administrative label portion of the PON-ID communicated in the PSBd field of the downstream frame within the target downstream wavelength channel does not match the Administrative label of the specified target downstream PON-ID.
3	DS	DS_LKTP	The optical link type communicated in the PSBd field of the downstream frame within the target downstream wavelength channel does not match ONU's link type (provided target downstream and upstream PON-IDs are identical).
4	US	US_ALBL	Based on the Channel_Profile parameters obtained in the target downstream wavelength channel, the Administrative label portion of the specified target upstream PON-ID does not match the learned Administrative label.
5	US	US_VOID	Based on the Channel_Profile parameters obtained in the target downstream wavelength channel, the descriptor of the specified target upstream wavelength channel is void.
6	US	US_TUNR	Based on the Channel_Profile parameters obtained in the target downstream wavelength channel, all the central wavelengths of the target upstream wavelength channel are outside of ONU's transmitter tuning range.
7	US	US_LKTP	Based on the Channel_Profile parameters obtained in the target downstream wavelength channel, the ONU's optical link type is not supported by the target upstream wavelength channel.
8	US	US_LNRT	Based on the Channel_Profile parameters obtained in the target downstream wavelength channel, the ONU's supported upstream line rate does not match the line rate of the target upstream wavelength channel.
9	US	US_LNCD	Based on the Channel_Profile parameters obtained in the target downstream wavelength channel, the ONU's supported upstream line code does not match the line code of the target upstream wavelength channel.

17.3.3 OLT wavelength channel handover state machine

In order to support the preplanned ONU handover between two TWDM channels, the OLT CTs should behave substantially in agreement with the state machine specified in this clause.

17.3.3.1 States, timers, inputs, and outputs

Table 17-5 summarizes OLT wavelength handover states.

Table 17-5 – OLT wavelength handover states

State	Semantics
Unaware	Default state for all ONU-IDs that are disassociated with the given OLT CT. The data structures pertaining to the ONU-ID are invalidated and may be de-allocated. These ONU-specific data structures are instantiated once the ONU announces itself in response to an open SN grant or once an ONU handover from another TWDM channel is negotiated via the ICTP channel.
Expecting	The OLT CT expects a handover of an ONU from another TWDM channel. The ONU-ID specific data structures are instantiated. Target OLT CT wait timer T_{target} is started upon entry to the state and stopped upon exiting the state. The OLT CT provides PLOAM-only allocations to the given ONU-ID on a regular basis, but does not react adversely to the missed allocations. The OLT CT may use increased guard times around the expected burst from the given ONU-ID to compensate for the equalization delay uncertainty. Receiving TuningResp (Complete_u) PLOAMu from the ONU-ID causes a transition to the Hosting state. Receiving ICTP notification, which indicates TuningResp (Rollback/NACK) from the Source OLT CT, causes a transition to the Unaware state. T_{target} expiration indicates a failure of the tuning procedure and leads to an ICTP alert which is broadcast to all TWDM channels.
Hosting	The ONU-ID is associated with the OLT CT, and is subject to regular PLOAM and date allocations and traffic forwarding in the upstream and downstream direction. If the state is entered upon failed handover, the OLT CT shall report the failure to the EMS and to the peer OLT CTs for the appropriate diagnostic steps to be performed.
Redirecting	The OLT CT instructs the ONU to schedule the start of the tuning procedure at a specified moment in the future. The ONU-ID is associated with the OLT CT, and is subject to regular PLOAM and data allocations and traffic forwarding in the upstream and downstream direction. Source OLT CT wait timer T_{source} is started upon entry to the state. The Tuning_Response PLOAM is expected with either ACK or NACK to determine the subsequent state transition. Receiving TuningResp (ACK) from the ONU causes a transition to the Seeing-Off state. Receiving TuningResp (NACK) from the ONU causes a transition to the Hosting state. T_{source} expiration which means the lack of the PLOAM response is handled like a LOB_i or $LOPC_i$ condition: the OLT CT transitions into the Hosting state for execution of corresponding in-channel mitigation procedures.
Seeing-Off	The OLT CT hands over of an ONU to another TWDM channel. The OLT CT provides PLOAM allocations to the given ONU-ID on a regular basis, as well as data allocation to drain any possibly fragmented SDUs prior to scheduled start of the tuning procedure, but does not react adversely to the missed allocations. An ICTP confirmation of the successful completion of the tuning procedure disassociates the ONU from the OLT CT, stops timer T_{source} and causes a transition to the Unaware state. If the OLT CT receives a rollback request from the ONU, the OLT CT returns to the Hosting state. If timer T_{source} expires without ICTP confirmation, the OLT returns to the Hosting state, but issues a broadcast ICTP alert against the ONU-ID.

Table 17-6 summarizes OLT wavelength handover timers.

Table 17-6 – OLT wavelength handover timers

Timer	Full name	State	Semantics and initial value
T_{source}	Source OLT wavelength handover wait timer	Redirecting, Seeing-Off	Timer T_{source} limits the duration of OLT CT's wait for the ONU to complete tuning after the Tune-Out handover transaction has been committed. This timer should be longer than T_{target}.
T_{target}	Target OLT wavelength handover wait timer	Expecting	Timer T_{target} limits the duration of OLT CT's wait for the ONU arrival after the Tune-In handover transaction has been committed.

Table 17-7 – OLT wavelength handover state machine inputs

Input	Applicable states	Semantics
ICTP events		
Tune-In (ONU-ID, Source DS PON-ID, Source US PON-ID)	Unaware	Commit indication of a transaction affirming a scheduled handover of an ONU identified by ONU-ID into the specified pair of downstream and upstream wavelength channels.
Tune-Out (ONU-ID, Target DS PON-ID, Target US PON-ID)	Hosting	Commit indication of a transaction affirming a scheduled handover of an ONU identified by ONU-ID out of the specified pair of downstream and upstream wavelength channels.
Confirm(ONU-ID)	Seeing-Off	Commit indication of a transaction confirming the successful arrival of the ONU identified by ONU-ID to another TWDM channel.
Abort (ONU-ID)	Expecting	An ICTP message from the Source OLT CT to the Target OLT CT indicating the failure of the handover procedure (the Source OLT CT has received either TuningResp (ACK) or TuningResp (Rollback) from the ONU-ID). The target OLT CT which receives Abort (ONU-ID) stops the timer T_{target}.
PLOAM events		
TuningResp (<opcode>, ONU-ID)	Unaware, Expecting, Hosting, Redirecting, Seeing-Off	Tuning_Response PLOAM message with the specified operation code received from ONU-ID. The operation code (<opcode>) can be either ACK, NACK, Complete_u or Rollback.
Timer events		
T_{source} expires	Seeing-Off	Timer expiration indicating a tuning procedure failure.
T_{target} expires	Expecting	Timer expiration indicating a tuning procedure failure.

Table 17-8 – OLT wavelength handover state machine outputs

Output	Semantics
ICTP events	
confHandover (ONU-ID)	An ICTP transaction between the Target OLT CT and the Source OLT CT confirming the successful arrival of the ONU identified by ONU-ID to the Target TWDM channel.
Alert (ONU-ID, Source DS PON-ID, Source US PON-ID)	A broadcast ICTP alert by the given OLT CT to all other OLT CTs in the TWDM system, to indicate an unspecified failure of the tuning procedure and requesting that the ONU with the specified ONU-ID be directed towards specified pair of downstream and upstream wavelength channels. In all failure cases, it is the Source OLT CT that should retain custody of the ONU, because the ONU is known to be able to work with the Source OLT CT, which is not the case for the Target OLT CT.
Abort (ONU-ID)	An ICTP message from the Source OLT CT to the Target OLT CT indicating the failure of the handover procedure (the Source OLT CT has received either TuningResp (ACK) or TuningResp (Rollback) from the ONU-ID). The target OLT CT which receives Abort (ONU-ID) stops the timer T_{target}.
PLOAM events	
TuningCtrl (<opcode>, ONU-ID, Target US PON-ID, Target DS PON-ID)	Tuning_Control PLOAM message with the specified operation code transmitted to ONU-ID. The operation code (<opcode>) can be either Request or Complete_d.

Tables 17-7 and 17-8 list the input and output events using the complete format with the associated parameters. In the OLT state diagram (clause 17.3.3.2) and OLT state transition table (clause 17.3.3.3) for ONU wavelength channel handover below, the specific ONU-ID and the specific pair of source and target wavelength channels associated with input and output events are omitted for clarity; only the relevant operation codes are shown. Abort() and Alert() are shorthand references for the ICTP messages abortHandover() and onuAlert(), respectively (see clause VI.2).

17.3.3.2 OLT tuning state diagram

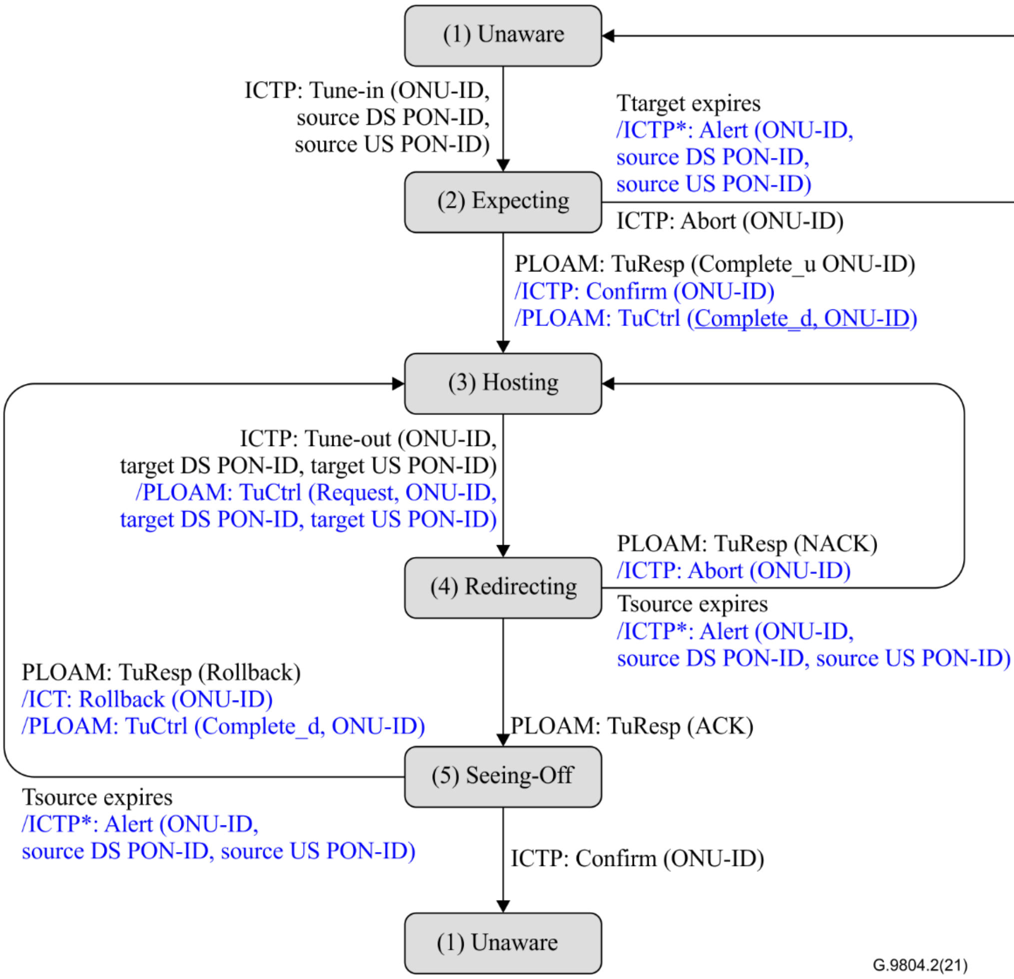


Figure 17-2 – OLT wavelength handover state transition diagram

In Figure 17-2, the slash (/) is used to distinguish the input event that triggers the state transition from the output action associated with the state transition (Mealy notation).

17.3.3.3 OLT state transition table

Table 17-9 – OLT state transition table

	(1) Unaware	(2) Expecting	(3) Hosting	(4) Redirecting	(5) Seeing-Off
Local activation	→ (3)	This event is recognized in Unaware state only			
ICTP:Tune-In ( )	Start T_{target} → (2)	Tune-in is a transaction and, therefore, should be rejected within the ICTP protocol. No input for the wavelength handover state machine is generated.			
ICTP:Tune-Out ( )		Rejected within the ICTP protocol	Start T_{source} TuningCtrl (Request) → (4)	Rejected within the ICT protocol	Rejected within the ICTP protocol

Table 17-9 – OLT state transition table

	(1) Unaware	(2) Expecting	(3) Hosting	(4) Redirecting	(5) Seeing-Off
ICTP:Confirm ( )		ICTP violation	ICTP violation	ICTP violation Stop T_{source} → (1)	Stop T_{source} → (1)
ICTP:Abort ( )		Stop T_{target} → (1)	ICTP violation	ICTP violation	ICTP violation
TuningResp (ACK)		PLOAM violation → (1)	PLOAM violation *	→ (5)	*
TuningResp (NACK)		PLOAM violation → (1)	*	Stop T_{source} ICTP: Abort ( ) → (3)	PLOAM violation Stop T_{source} ICTP:Alert ( ) → (3)
TuningResp (Rollback)		PLOAM violation → (1)	PLOAM violation *	PLOAM violation Stop T_{source} → (3)	Stop T_{source} ICTP:Abort ( ) TuningCtrl (Complete_d) → (3)
TuningResp (Complete_u)		Stop T_{target} ICTP:Confirm( ) TuningCtrl (Complete_d) → (3)	*	PLOAM violation Stop T_{source} ICTP:Alert ( ) → (3)	PLOAM violation Stop T_{source} ICTP:Alert ( ) TuningCtrl (Complete_d) → (3)
T_{target} expires		ICTP:Alert ( ) → (1)			
T_{source} expires				ICTP:Alert ( ) → (3)	ICTP:Alert ( ) → (3)

NOTE – Grey shading indicates that an event is not applicable in the given state. Yellow shading indicates either PLOAM or ICTP protocol violation. An asterisk "*" means that the state machine stays in the same state.

In Table 17-9, the actions listed for the cells marked PLOAM violation or ICTP violation are mere suggestions based on the likely underlying events. The complete mitigation action is at the OLT CT discretion. The OLT CT takes into account additional factors such as the LOB_i condition (current and intermittent), PLOAM sequence number value, and state of the security association with the sender, and checks the observed violation for possible signs of the ONU cloning attack. The OLT CT should make a record of the violation, incrementing an appropriate event counter, and may either leave it inconsequential, or take proactive steps including, but not limited to, raising an alarm to OSS, alerting other OLT CTs in the system about a run-away/duplicate ONU, re-authenticating, deactivating or disabling the ONU, or executing a rogue ONU diagnostic procedure. As an example, on receipt of ICTP:Confirm message while in the Redirecting state for a given ONU-ID, the OLT CT may check whether the ONU is in LOB_i, and if so, presume a loss of Tuning ACK, increment the $LOPC_i$ counter, stop the T_{source} timer and transition into the Unaware state.

17.4 TWDM ONU wavelength channel locking

For the ONUs supporting fine wavelength tuning, the OLT CT may provide closed loop upstream wavelength control through a dithering mechanism: the OLT CT requests small Tx wavelength adjustments and monitors the quality parameters of the received optical signal. By implementing upstream wavelength dithering, the OLT CT ensures stability of the ONU's transmission wavelength, or in other words, locks the ONU to the upstream wavelength channel.

Apart from the regular transmission of Adjust_Tx_Wavelength PLOAM messages by the OLT CT, the ONU wavelength channel locking does not require any real-time signalling information exchange, but the OLT CT must be aware of the tuning capabilities of the ONU. The ONU reports its tuning capabilities within the Serial_Number_ONU PLOAM message and the Tuning_Response(Complete_u) PLOAM message.

The ONU's tuning/dithering capability report includes:

– The tuning granularity of the ONU: the largest applicable value over the operating frequency band and the upstream rate, expressed in GHz. The tuning granularity of the ONU should be equal to or finer than the tuning granularity specified for the particular upstream interface in clause 11.1.4 of [ITU-T G.989.2].
– The tuning time for a single granularity step: the largest value over the operating frequency band and the tuning direction. The reported tuning time corresponds to reaching at least 90% of full granularity step, includes all significant transients, and is expressed in the units of PHY frames.

Assume that an ONU has reported the tuning time of T PHY frames per tuning granularity step. If in PHY frame F, the OLT CT requests the adjustment of the upstream wavelength in the amount equivalent to N granularity steps, it may start collecting the optical signal quality statistics in PHY frame $F + N \times T + 6$. The fixed shift of 6 PHY frames (equivalent to 750 µs) represents the normative processing time of a PLOAM message.

The ONU that follows the Adjust_Tx_Wavelength PLOAM instructions modifies its calibration record for the operating upstream wavelength channel accordingly.

17.5 Temporary suspension of a bonded wavelength channel

In a TWDM system, a legitimate need may arise to temporarily withdraw one or several chosen wavelength channels from operation. The possible legitimate reasons for wavelength channel withdrawal include maintenance, software or hardware upgrade, and power saving. When so is the case, the key operational requirement is to avoid or minimize the disturbance to the services that use the chosen wavelength channel.

In a conventional TWDM PON system, service disturbance is minimized by executing wavelength channel handover out of the chosen channel for all ONU using that channel.

In a TWDM system that supports wavelength channel bonding, the service disturbance to a bonded service (other than reduction of the available digital bandwidth) can be avoided, as long as at least one wavelength channel remains in operation, by gracefully distributing the traffic load among the remaining wavelength channels. The act of withdrawing a wavelength channel from operation for a bonded service and reinstating the wavelength channel for bonded service is referred to as Suspend and Bond, respectively.

To Suspend or Bond a chosen wavelength channel, a pair of PLOAM messages is used: a downstream "Bonded_Channel_Status" PLOAM message (see clause 11.3.3.20), and an upstream "Bonded_Channels_Response" PLOAM message (see clause 11.3.4.8). Conceptually, the Suspend and Bond instructions are processed by the Channel Selection Function (CSF) of a bonded ONU device and impact the upstream CSF operation only. The downstream CSF operation is not impacted, as traffic dispatch in the downstream direction is controlled by the OLT side.

A suspended wavelength channel remains in the O5 state of the activation cycle state machine and is fully functional from the OAM perspective. Once a chosen wavelength channel is suspended, the further OAM operations on this channel are supported by the conventional PLOAM and OMCI functions.

Note specifically the use case of placing a chosen ONU wavelength channel into the watchful sleep mode for the power saving purposes (assuming per-channel watchful sleep control). It is possible to skip the periodic checking of the FWI signal while the ONU state machine is in its LowPower state, as the FWI signal is effectively delivered by the Bond instruction carried in one of wavelength channels remaining in operation. The exact method of FWI delivery may impact the suspended channel restoration time, and is a subject to service requirements.

18 TWDM system protection

18.1 OLT CT coordination in 1:1 Type B protection

The 1:1 Type B protection configuration involves a single channel group where each individual channel pair has two OLT channel terminations. Figure 18-1 shows a dual-parented Type B protection configuration, where the OLT CTs terminating a protected channel pair are housed in different OLT chassis. The only difference between the dual-parented configuration shown in Figure 18-1 and the single-parented configuration, is that the two OLT channel terminations associated with a channel pair in the latter configuration belong to the same OLT chassis and have the possibility to share the same SNI. The two OLT CTs terminating the same protected channel pair are mutually known as Type B peers.

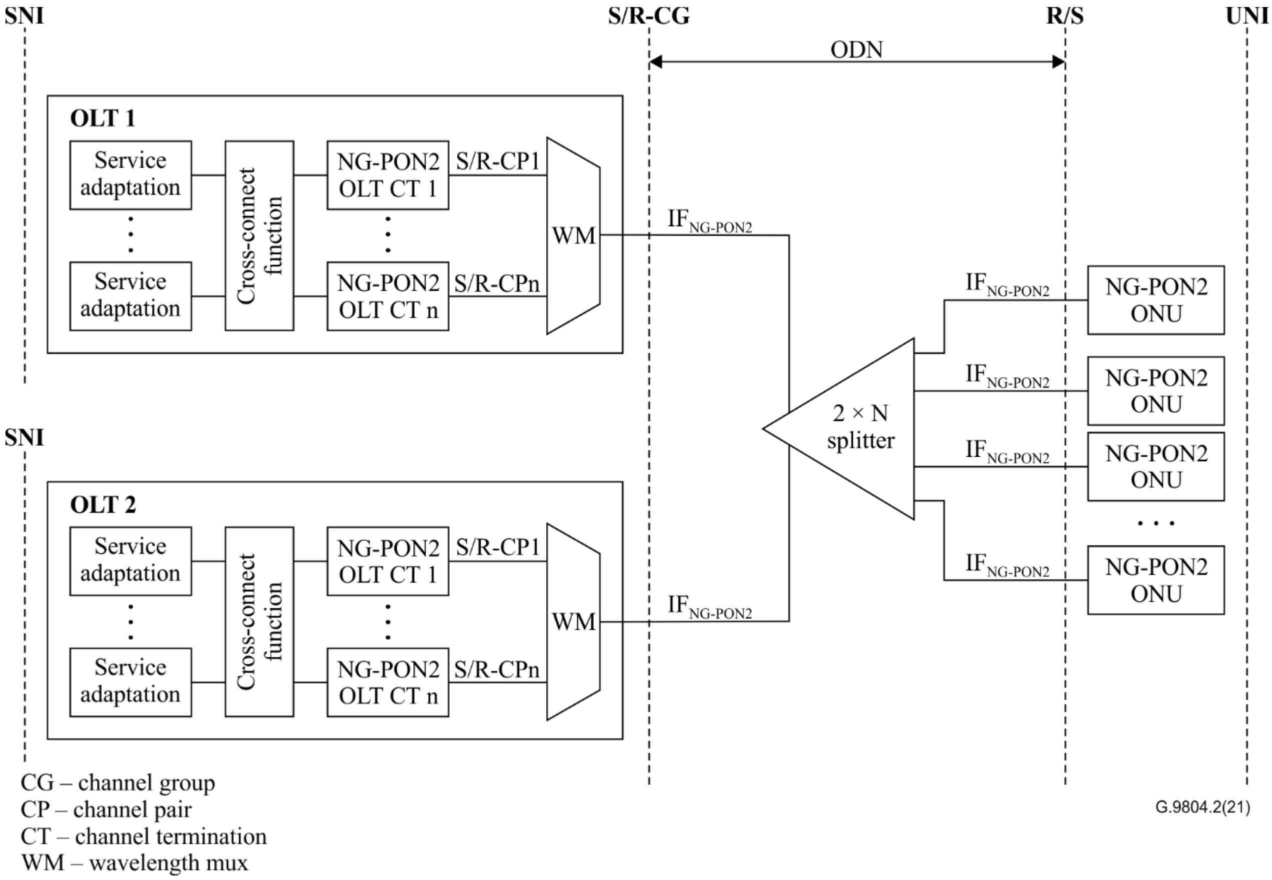


Figure 18-1 – 1:1 Type B dual parenting protection configuration

The Type B protection configuration allows to mitigate a fault in the channel attachment fibre (i.e., the fibre segment between the OLT CT and the WM) or in the feeder fibre (between the WM and the splitter), as well as a failure of the WM, of the OLT CT itself and, in case of dual parenting, of the entire OLT chassis. Each channel pair is protected independently. In case of a feeder fibre fault or a WM or chassis failure, all individual protected channel pairs within the channel group are switched simultaneously. If an individual OLT CT fails or a fault occurs in the attachment fibre, only the affected channel pair is switched, while the other channel pairs within a channel group are not impacted.

The Type B protection does not require ONU tuning: in the course of a protection switching event, the ONU connectivity is maintained using one and the same channel pair. Therefore, for the Type B protection to be effective, the downstream synchronization needs to be restored before an ONU makes a retuning decision.

The two OLT CTs associated with the same channel pair need to coordinate their status in order to avoid transmitting simultaneously at any time. To that goal, each OLT CT needs to run a state machine as specified in clause 18.2. This state machine also supports the silent start behaviour, as described in clause 19.3.2.

Type B protection mechanism for a TWDM channel pair ensures that as long as at least one OLT CT is available, exactly one OLT CT assumes the Active role, transmitting optical signal in the downstream direction and providing service to the ONUs, whereas the other OLT CT, if available, assumes the Standby role, monitoring the upstream transmissions and being ready to take over if a failure prevents the peer OLT CT from continuing in the Active role.

Each OLT CT of a protected channel pair is configured with the default role of either Primary OLT CT or Secondary OLT CT. The Primary OLT CT assumes the Active role for the protected channel pair if it has necessary service configuration for the attached ONUs, and is not experiencing a communication or equipment failure. The Secondary OLT CT assumes the Active role for the protected channel pair if it has necessary service configuration for the attached ONUs, is not experiencing a communication or equipment failure, and the Primary OLT CT is not available to assume the Active role. The OLT CTs terminating a protected channel pair resolve their operation protection roles in the course of an ICTP handshake.

In a revertive Type B protection configuration, the default roles are persistent. In a non-revertive Type B protection configuration, the OLT CT effectively abandons its default role once an ICTP handshake is completed.

18.2 OLT CT Type B protection state machine

The OLT CT Type B protection state machine specified in this clause accepts timer events, management events, ComTC layer events, and ICTP events. However, it is designed to make progress and maintain consistency in the absence of ICTP event input as well, for example, in the situations when the ICTP transport infrastructure is not functional.

18.2.1 States

Table 18-1 provides OLT CT Type B protection state machine states.

Table 18-1 – OLT CT Type B protection states

State	Semantics
Initialization	The initial state of the state machine. The OLT CT is provisioned as part of a Type B protection configuration. The OLT CT starts Tsstart timer and periodically sends ICTP:Peering() message initiating an ICTP handshake with the Type B peer to resolve the effective role in the protection arrangement, based on the current state of the system and the default role designation as Primary or Secondary. The optical transmitter is turned off.
Pre-Protecting	The re-initialized OLT CT has received an upstream transmission, indicating that another OLT CT is active on the same wavelength channel pair. Tsstart timer is stopped. The OLT CT periodically sends ICTP:Peering() message initiating an ICTP handshake with the Type B peer to resolve the role in the protection arrangement. The T_{ictp} timer is started. The optical transmitter is turned off.
Protecting	The OLT CT has assumed the Standby role, while the peer OLT CT controls the wavelength channel pair. The optical transmitter is turned off. The OLT CT is not expected to support execution of the per-ONU state machines. The OLT CT may obtain service information from the Active OLT CT.
LOS-P	The OLT CT in the Standby role has detected a simple LOS condition. The OLT CT starts Tpfail timer, periodically sends ICTP:Peering( ) to the Type B peer to inquire about the potential role switching. The optical transmitter is turned off. The OLT CT is not expected to support execution of the per-ONU state machines.
Pre-Working	The OLT CT has assumed the Active role, turned its transmitter on and commenced downstream transmission, looking to confirm that its signal is received by the ONUs. The T_{hold} timer with the scope covering the states (5) through (7) is started to guarantee a minimum time in the Active role. The T_{ract} timer is started to limit the time the OLT CT awaits for its Active role to be confirmed by a proper upstream transmission.
Working	The OLT CT in the Active role has received a confirmation through a proper upstream transmission that its signal is received and processed. The OLT CT controls the wavelength channel pair.

Table 18-1 – OLT CT Type B protection states

State	Semantics
LOS-W	The OLT CT in the Active role has detected a qualified LOS condition, starts T_{wfail} timer, continues transmitting downstream. Unless the LOS condition is cleared, the OLT CT remains in the LOS-W state until expiration of both T_{wfail} and T_{hold} timers.
Helpme	The OLT CT periodically sends the ICTP:Active( ) message to request its Type B peer to execute protection switching and to take control over the channel pair. The T_{ictp} timer is started. The optical transmitter is turned off.
COMM-FAIL	The OLT CT has detected a fault condition whereby it observes no upstream traffic, while the upstream transmissions either are expected based on OLT CT's own downstream transmissions, or have been confirmed by the peer OLT CT. This condition may be attributed to a fibre cut or a silent transceiver failure.
EQPT-FAIL	The OLT CT has detected a major local equipment failure that warrants immediate protection switching to the peer OLT CT, and prevents further participation of this OLT CT in the protection scheme. The peer OLT CT subsequently executing an ICTP handshake receives ICTP:Unprotected( ) indication.

18.2.2 Timers

Table 18-2 provides a list the OLT CT Type B protection state timers.

Table 18-2 – OLT CT Type B protection state timers

Timer	Full name	State	Semantics and initial value
T_{sstart}	Silent start timer	Initialization	The duration of time a re-initialized OLT CT waits before assuming the Active role by default. The timer is started upon transition into the Initialization state. If an upstream transmission is detected, the timer is stopped. The expiration of the timer drives transition into the Pre-Working state. The initial value of T_{sstart} equals to the maximum ICTP response time with appropriate safety margin.
T_{pfail}	Protecting state failure timer	LOS-P	The elapsed time between LOS declaration in the Protecting state and the decision to execute protection switching. The timer is started upon entry into the LOS-P state after the LOS declaration in the Protecting state. The timer is restarted once ICTP:Standby-LOS( ) is received. The expiration of the timer drives a transition into the Pre-Working sate. The initial value of T_{pfail} equals to the maximum ICTP response time with appropriate safety margin.
T_{ract}	Receiver active confirmation timer	Pre-Working	The maximum time an OLT CT attempts to attain control over the ONUs attached to the wavelength channel pair. The timer is started upon entry into the Pre-Working state and is stopped once any upstream transmission consistent with the bandwidth map is received. The expiration of the timer indicates a possible fibre cut or a silent transceiver failure.

Table 18-2 – OLT CT Type B protection state timers

Timer	Full name	State	Semantics and initial value
T_{hold}	Working state hold timer	Working, LOS-W	The duration of the time interval for which a transition lock is imposed on an OLT CT that has just entered the Working state. The timer is started upon entry into the Working state from the LOS-P state and is run until expiration through the Working and LOS-W states. The expiration of the timer is a precondition for a transition into the Helpme state.
T_{wfail}	Working state failure timer	LOS-W	The elapsed time between LOS declaration in the Working state and the decision to appeal to the peer OLT CT for protection. The timer is started upon entry into the LOS-W state. The expiration of the timer is a precondition for a transition into the Helpme state.
T_{ictp}	ICTP interaction timer	Pre-Protecting, Helpme	The timer applies in the states that involve an ICTP message exchange, ensuring state machine progress in case of a hypothetical ICTP infrastructure failure.

18.2.3 Events

Table 18-3 provides a list of OLT CT Type B protection state events.

Table 18-3 – OLT CT Type B protection state events

Event	Semantics
SLOS	Simple Loss of Signal. The event is recognized in the states where no downstream transmission occurs upon detection of 0.5ms (4 x 125 μs) of silence in the upstream direction.
QLOS	Qualified Loss of Signal. The event is recognized in the states where the OLT CT transmits in the downstream direction and supports per-ONU state machines execution. The event corresponds to four consecutive frames with no upstream transmission and declaration of LOBi for all relevant ONUs. The event is subject to exclusion based on the ONU population size, power management state machines, and Dying Gasp declarations by individual ONUs. In case, a legitimate exclusion blocks the QLOS event recognition, an ICTP:Standby-LOS() is sent periodically to the peer OLT CT.
LOS cleared	Loss of Signal Cleared. The event is recognized when an upstream burst received. In the states where the OLT CT transmits in the downstream direction and supports per-ONU state machines execution, the burst needs to be consistent with the bandwidth map.
ICTP: Active( )	The recipient OLT CT is declared Active as a result of the ICTP role handshake.
ICTP: Standby-LOS( )	The recipient OLT CT is declared Standby as a result of the ICTP role handshake, but is warned to abstain from executing protection switching based solely on timer expiration as no upstream transmission is expected.
ICTP: Standby-Clear( )	The recipient OLT CT is declared Standby as a result of the ICTP role handshake, and is informed that the Type B peer successfully transmits downstream and receives upstream transmissions.
EMS: Forced( )	This is an upper layer management event which is recognized in the Working state only. The OLT CT is instructed to abandon the Active role and to hand over control over the wavelength channel pair to the peer OLT CT.

Table 18-3 – OLT CT Type B protection state events

Event	Semantics
EMS: CTreset( )	This is an upper layer management event which is recognized in any state, but is instrumental in COMM-FAIL and EQPT-FAIL states only.

18.2.4 State transition diagram

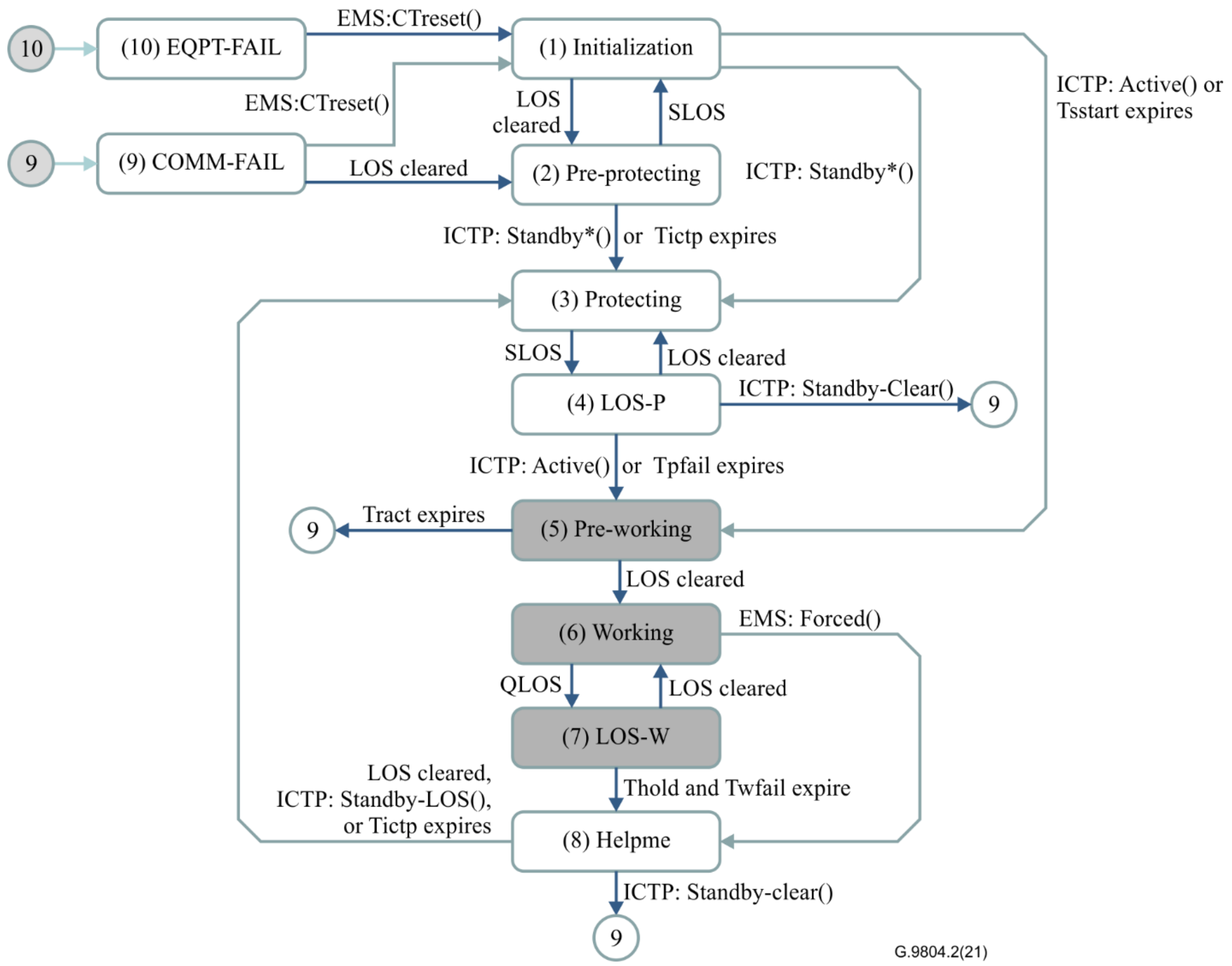


Figure 18-2 – OLT CT Type B protection state transition diagram

Figure 18-2 illustrates the OLT CT Type B protection state transition diagram. The states in which the OLT CT is in Active role transmitting downstream are shaded.

The solid blue entry points indicate: for the COMM-FAIL state, a transition upon occurrence of any of the three events marked with (9); for EQPT-FAIL, a transition from any state upon detection of a local equipment failure.

18.2.5 State transition table

Table 18-4 provides the OLT CT Type B protection state transition table.

Table 18-4 – OLT CT Type B protection state transition table

Inputs	States									
	(1) Initialization	**(2) Pre-Protecting**	**(3) Protecting**	**(4) LOS-P**	**(5) Pre-Working**	**(6) Working**	**(7) LOS-W**	**(8) HelpMe**	**(9) COMM-FAIL**	**(10) EQPT-FAIL**
SLOS	*	Stop T_{ictp}; →(1)	→(4) Start T_{pfail};	*				*	*	*
QLOS					*	→(7) Start T_{wfail};	*			
LOS cleared	Stop T_{sstart}; →(2) Start T_{ictp};	*	*	→(3)	Stop T_{ract}; →(6) Start T_{hold};	*	Stop T_{wfail}; →(6)	Stop T_{ictp}; →(3)	→(2) Start T_{ictp};	*
T_{sstart}	→(5) Start T_{ract};									
T_{pfail}				→(5) Start T_{ract};						
T_{hold}&T_{wfail}							→(8) Start T_{ictp};			
T_{ract}					→(9)					
T_{ictp}		→(3)						→(3)		
Active()	Stop T_{sstart}; →(5) Start T_{ract};	* (Note1)	* (Note 1)	Stop T_{pfail}; →(5) Start T_{ract};	*	*	*	(Note 3)	*	*
Standby-LOS()	Stop T_{sstart}; →(3)	Stop T_{ictp}; →(3)	*	* Reset T_{pfail};	(Note 2)	(Note 2)	(Note 2)	Stop T_{ictp}; →(3)	*	*
Standby-Clear()	Stop T_{sstart}; →(3)	Stop T_{ictp}; →(3)	*	Stop T_{pfail}; →(9)	(Note 2)	(Note 2)	(Note 2)	Stop T_{ictp}; →(9)	*	*
EQPT failure	Stop T_{sstart}; →(10)	Stop T_{ictp}; →(10)	→(10)	Stop T_{pfail}; →(10)	→(10)	Stop T_{hold}; →(10)	Stop T_{hold},T_{wfail}; →(10)	Stop T_{ictp}; →(10)	→(10)	→(10)

Table 18-4 – OLT CT Type B protection state transition table

Inputs	States									
	(1) Initialization	**(2) Pre-Protecting**	**(3) Protecting**	**(4) LOS-P**	**(5) Pre-Working**	**(6) Working**	**(7) LOS-W**	**(8) HelpMe**	**(9) COMM-FAIL**	**(10) EQPT-FAIL**
CTreset	* Reset T_{sstart};	Stop T_{ictp}; →(1) Start T_{sstart};	→(1) Start T_{sstart};	Stop T_{pfail}; →(1) Start T_{sstart};	→(1) Start T_{sstart};	Stop T_{hold}; →(1) Start T_{sstart};	Stop T_{hold},T_{wfail}; →(1) Start T_{sstart};	Stop T_{ictp}; →(1) Start T_{sstart};	→(1) Start T_{sstart};	→(1) Start T_{sstart};
Forced						→(8) Start T_{ictp};				

Table notation – An asterisk denotes a self-transition; shading indicates an impossible event or protocol violation.

NOTE 1 – This is likely a race condition, which should have not occurred if the ICTP:Active() message had been generated prudently. Wait for SLOS to be declared and follow the ICTP:Active() transition at the SLOS event target state. If SLOS is not declared, ignore the event.

NOTE 2 – This is a protocol violation. Report the occurrence, turn off transmitter, and make a transition into the Initialization state to repeat Type B role handshake.

NOTE 3 – This is a protocol violation. Report the occurrence and make a transition into the Initialization state to repeat Type B role handshake.

The ICTP:Peering() message does not lead to a state machine transition. Instead, the recipient OLT CT uses the reported information to resolve its own Type B protection role and responds with either ICTP:Active (), ICTP:Standby-LOS(), or ICTP:Standby-Clear(), which do drive the state machine transitions.

The OLT CT receiving an ICTP:Unprotected() indication from a failed Type B peer sets the initial value of the Tpfail timer to infinity and continues the regular state machine execution. The initial value of the Tpfail timer is set back to an appropriate finite value upon receipt of a ICTP:Peering() message from a previously failed OLT CT.

Timers Tstart and Tpfail have relatively large initial values. In case the ICTP channel is available between the Working and Protection CTs, both these timers should accommodate an ICTP message turnaround time with a reasonable margin. If the ICTP channel is not available, these two timers should remain the largest among those specified in this clause. To avoid the situation when the Protecting OLT CT declares a protection switching event and starts transmitting before the Working OLT CT ceases its transmission, the following two conditions in the initial values of the timers should be met:

Tpfail > Thold;

Tpfail > Twfail.

In order for the holding feature to make operational sense, the following should be maintained true:

Thold > Twfail.

Setting otherwise effectively disables the holding feature. Finally, Tract has relatively small initial value comparable with the PON grant response time. A reasonable initial value for Tract is 1.5 ms.

18.3 Simplified state transition diagram

In case when the ICTP transport infrastructure is known to be not functional, the state transition diagram can assume a simplified form shown in Figure 18-3. The T_{ictp} timer can be set to zero. The Pre-Working and Helpme states in this case become degenerate pass-through states.

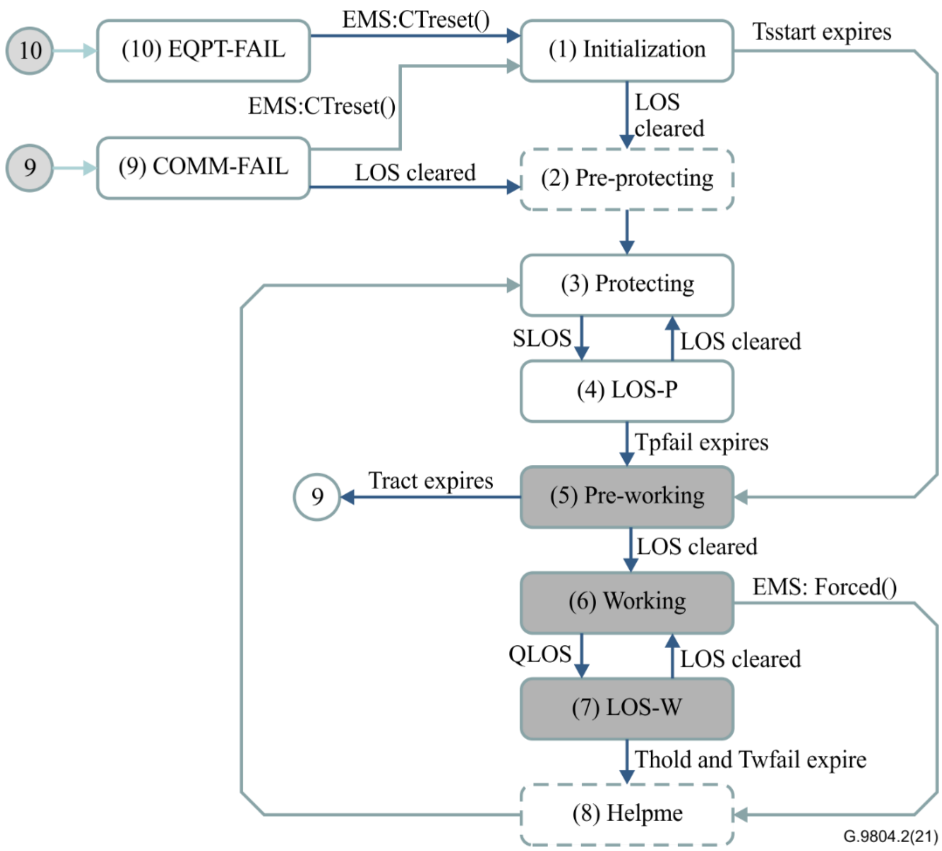


Figure 18-3 – Simplified OLT CT Type B protection state transition diagram

19 Rogue behaviour and its mitigation

This clause is largely concerned with rogue behaviour models directly associated with TDMA, the multi-wavelength nature of TWDM, and coexistence with legacy ONUs. This clause does not specify any interoperation between an OLT and an ONU. For the examples of specific mitigation techniques, see [b-ITU-T G-sup.49].

19.1 Rogue ONU behaviour model

Rogue ONU mitigation is intended to protect against the following rogue behaviour models:

a) In TDM and TWDM, an ONU transmits in the wrong time slot in its upstream wavelength channel, and interferes with other ONU's upstream transmission in the same upstream wavelength channel. Root cause may be various, referring to [b-ITU-T G-sup.49]. The OLT detects LOB_i in the wavelength channel.

b) In TWDM, an ONU TX hops and transmits in the wrong upstream wavelength channel. Associated OLT channel termination detects the LOB_i while one or more affected channel terminations detect the interference signal.

c) In TWDM, an ONU TX tunes wrongly to a non-target upstream wavelength channel. Both source OLT channel termination and target OLT channel termination fail to discover the ONU, while one affected OLT channel termination detects the interference signal.

19.2 Behaviour model when coexisting with legacy ONUs

19.2.1 Silent start at the ONU

In a coexistence scenario, rogue behaviour might be caused by ONUs from a PON system not controlled by the OLT. If such ONUs are able to transmit without being granted permission from an OLT, they may cause rogue events even though they are not faulty.

19.2.2 Silent start at the channel termination (OLT port)

Transmissions by an OLT CT might adversely affect ONUs of its own or a coexisting system.

It is recommended that upon new wavelength channel provisioning and any re-initialization an OLT CT implements "silent start" behaviour.

The silent start behaviour follows the state machine of clause 18 and is assured in the Initialization state by either blocking on Tsstart timer, or, if an upstream transmission is detected, by transitioning into the protection branch of the state machine.

19.2.3 Channel termination (OLT port) detection of rogue devices

In a coexistence scenario, rogue behaviour might be caused by ONUs from a PON system not controlled by the OLT. Isolation and mitigation of the rogue behaviour may be difficult or impossible.

19.3 Protection from noise and alien ONUs

An OLT CT that receives a signal during a quiet window shall consider that signal valid only if the received PSBu structure is valid. If, during a quiet window, an OLT CT receives a signal that does not contain a valid PSBu pattern, it may try to adjust its clock and data recovery to isolate the troublesome signal, or report an unexpected light detection event.

19.4 Troublesome ONU presence detection enabled through idle window

An OLT CT may create an idle window by temporarily withholding all allocations, including regular data PLOAM grants, ranging grants, and serial number grants.

By opening an idle window, the OLT CT is able to cyclically check the absence of most frequent troublesome transmitters wrongly connected to the PON fibre terminations: ONU point to point modems that do not implement ONU silent start; since they do not understand the downstream protocol, they generally transmit unconditionally, some of them just testing that there is incoming optical power. Since the optical windows might overlap in some future, such a feature will enhance resistance of HSP.

The idle window here corresponds to an upstream listening period by the OLT CT within its receiving optical wavelength window, when no Alloc-ID is given to any ONU or during an idle window opened when no broadcast PLOAM is sent downstream that would enable regular ONU to reply with a Serial_Number_ONU message.

This enables the OLT CT to recognize any upstream power received as an unexpected transmitter mis-connected to HSP and prompt the operator to undertake a corrective action.

Annex A

Hybrid error control (HEC) decoding and scrambler sequence codes

(This annex forms an integral part of this Recommendation.)

This is the same as Annex A of [ITU-T G.987.3].

Annex B

Forward error correction

(This annex forms an integral part of this Recommendation.)

B.1 Low density parity check (LDPC) codes

The material presented in B.1 is based on [b-IEEE 802.3ca].

B.1.1 LDPC Coding

The LDPC FEC encoding scheme is shown in Figure B.1. The scheme consists of a systematic LDPC encoder and a shortening and puncturing mechanism. Puncturing discards some of the parity-check bits to achieve a higher code rate (R). The parameters of the FEC coding scheme are:

– the LDPC parity-check matrix, $\boldsymbol{H}$;
– the number of transmitted information bits, K;
– the number of shortened information bits, S;
– the number of punctured parity-check bits, P;
– the number of parity-check bits after puncturing, M;
– the length of the FEC encoder output, $N = K + M$;
– the code rate, $R = K / N$, defined as the code rate after puncturing and after shortening.

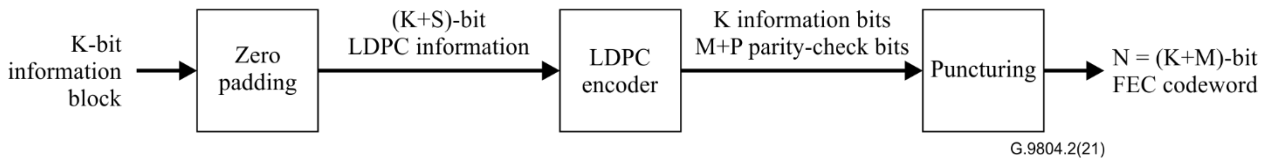


Figure B.1 – LDPC encoder

B.1.1.1 Encoding operation

The encoding process shall be as follows:

1) A group of K information bits $\boldsymbol{u} = [u_0, u_1, \cdots, u_{k-1}]$ are collected and copied to the output of the encoder to form a block of systematic code bits.

2) A total of S zero padding bits are appended at the end of u to form the full-length information bit block $\boldsymbol{u}^* = [\boldsymbol{u} \mid 0, \cdots, 0]$.

3) $M + P$ parity-check bits, $\boldsymbol{p} = [p_0, p_1, \cdots, p_{M-1} \mid p_M, \cdots, p_{M+P-1}]$, are computed using the parity-check matrix $\boldsymbol{H}$ and the information block $\boldsymbol{u}^*$. The resulting coded block $\boldsymbol{v}^* = [\boldsymbol{u}^* \mid \boldsymbol{p}]$ shall satisfy the parity check equations $\boldsymbol{v}^*\boldsymbol{H}^{\boldsymbol{T}} = \boldsymbol{0}$. Here, $\boldsymbol{0}$ is a zero row vector of dimension $M + P$.

4) The $M + P$ parity check bits $\boldsymbol{p}$ are copied to the output of the encoder as a block of parity-check bits $\boldsymbol{p} = [p_0, p_1, \cdots, p_{M+P-1}]$ to form the output coded block $\boldsymbol{v} = [\boldsymbol{u} \mid \boldsymbol{p}] = [v_0, v_1, \cdots, v_{K+M+P-1}]$.

5) The output of the encoder $\boldsymbol{v}$ is the input to the puncturing block (see Figure B-1). Last P parity bits are truncated.

NOTE – One method of encoding is to determine a systematic generator matrix $\boldsymbol{G}$ from $\boldsymbol{H}$ such that $\boldsymbol{G}\boldsymbol{H}^{\boldsymbol{T}} = \boldsymbol{0}$. A ($K$+$S$)-bit information block $\boldsymbol{u}^* = [u_0, u_1, \cdots, u_{k-1} \mid 0, \cdots, 0]$ can be encoded by the systematic generator matrix $\boldsymbol{G}$ via the operation $\boldsymbol{v}^* = \boldsymbol{u}^*\boldsymbol{G}$ to become a (K+S+M+P)-bit coded block $\boldsymbol{v}^* = [v_0, v_1, \cdots, v_{K+S+M+P-1}] = [\boldsymbol{u}^* \mid \boldsymbol{p}]$, where $\boldsymbol{p} = [p_0, p_1, \cdots, p_{M+P-1}]$ are the parity-check bits. The LDPC codes specified here are such that very low complexity encoding directly from $\boldsymbol{H}$ is possible.

B.1.2 Mother code parity check matrix

The full LDPC code is defined by a $(M + P) \times (K + S + M + P) = 3{,}072 \times 17{,}664$ size parity-check matrix $\boldsymbol{H}$, composed by an array of 12×69 circulant 256×256 sub-matrices $\boldsymbol{A_{i,j}}$:

$$\boldsymbol{H} = \begin{bmatrix} \boldsymbol{A_{1,1}} & \cdots & \boldsymbol{A_{1,69}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{A_{12,1}} & \cdots & \boldsymbol{A_{12,69}} \end{bmatrix}$$

The sub-matrices $\boldsymbol{A_{i,j}}$ are either a cyclic shifted version of the identity matrix or a zero matrix and have a size of 256×256. The parity-check matrix is described in its compact form:

$$\boldsymbol{H_c} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,69} \\ \vdots & \ddots & \vdots \\ a_{12,1} & \cdots & a_{12,69} \end{bmatrix}$$

A zero sub-matrix in position (i,j) is labelled with $a_{i,j} = -1$, and a rotated identity sub-matrix is labelled with a positive integer number $a_{i,j}$ defining the number of right column shifts of the identity matrix.

The LDPC parity-check matrix used in this Recommendation is identical to the matrix used in [b-IEEE 802.3ca] clause 142.2.4. The compact form of the parity-check matrix $\boldsymbol{H_c}$ is:

C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
80	−1	−1	105	−1	-1	137	−1	−1	0	209	53
−1	0	91	−1	170	46	−1	118	208	−1	−1	−1
−1	−1	−1	−1	250	−1	104	15	0	−1	252	93
60	0	74	87	−1	37	−1	−1	−1	123	−1	−1
169	−1	−1	−1	−1	−1	238	93	0	−1	39	216
−1	0	237	43	195	49	−1	−1	−1	41	−1	−1
11	−1	202	−1	139	150	−1	−1	0	191	−1	−1
−1	0	−1	165	−1	−1	228	228	−1	−1	159	57
143	−1	−1	−1	−1	65	−1	−1	0	211	69	9
−1	0	201	180	135	−1	225	78	−1	−1	−1	−1
−1	−1	136	−1	−1	−1	247	−1	0	217	37	130
222	0	−1	80	92	177	−1	16	−1	−1	−1	−1
−1	−1	178	227	−1	144	−1	0	−1	243	134	−1
59	0	−1	−1	147	−1	191	−1	251	−1	−1	130
−1	−1	239	221	−1	70	−1	48	0	97	−1	−1
218	0	−1	−1	1	−1	177	−1	−1	−1	201	238
−1	−1	183	77	−1	95	−1	0	−1	252	49	−1
−1	0	−1	−1	−1	−1	255	−1	44	−1	−1	−1
178	0	−1	−1	−1	−1	−1	−1	123	−1	−1	−1
−1	−1	217	0	−1	221	−1	−1	−1	−1	−1	−1
−1	0	−1	−1	13	−1	−1	62	−1	−1	−1	−1
−1	−1	232	−1	−1	−1	−1	−1	−1	0	104	−1
−1	−1	−1	−1	−1	−1	192	0	−1	−1	−1	144
−1	−1	−1	−1	98	192	−1	−1	0	−1	−1	−1
105	0	−1	16	−1	−1	−1	−1	−1	−1	−1	−1
−1	−1	169	−1	−1	128	−1	0	−1	−1	−1	−1

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
−1	−1	−1	−1	142	−1	−1	−1	0	−1	129	−1
19	0	−1	−1	−1	−1	51	−1	−1	−1	−1	−1
−1	−1	−1	−1	−1	214	−1	−1	−1	0	−1	162
−1	−1	−1	252	−1	−1	−1	−1	−1	−1	157	0
126	−1	−1	−1	225	−1	−1	0	−1	−1	−1	−1
−1	−1	−1	96	−1	−1	−1	−1	0	41	−1	−1
−1	0	129	−1	−1	−1	195	−1	−1	−1	−1	−1
−1	−1	60	0	−1	−1	−1	−1	−1	−1	222	−1
211	−1	−1	−1	−1	51	0	−1	−1	−1	−1	−1
−1	−1	−1	−1	−1	−1	−1	−1	0	29	−1	175
−1	0	−1	−1	23	−1	−1	112	−1	−1	−1	−1
−1	−1	−1	−1	108	−1	172	−1	−1	0	−1	−1
−1	−1	−1	17	−1	100	−1	0	−1	−1	−1	−1
−1	0	19	−1	−1	−1	−1	−1	−1	−1	−1	145
247	−1	76	−1	−1	−1	−1	−1	0	−1	−1	−1
−1	−1	−1	−1	−1	19	−1	−1	−1	−1	139	0
255	−1	−1	−1	−1	−1	−1	−1	−1	0	39	−1
−1	0	−1	−1	−1	−1	219	−1	153	−1	−1	−1
−1	−1	−1	219	0	235	−1	−1	−1	−1	−1	−1
85	−1	−1	−1	−1	−1	−1	0	−1	−1	−1	36
−1	−1	77	−1	0	−1	236	−1	−1	−1	−1	−1
−1	0	−1	198	−1	−1	−1	−1	−1	193	−1	−1
−1	−1	−1	165	−1	−1	−1	−1	0	−1	203	−1
−1	−1	−1	−1	−1	−1	136	0	−1	145	−1	−1
−1	−1	2	−1	−1	−1	−1	0	−1	−1	94	−1
−1	−1	−1	−1	135	−1	−1	−1	0	−1	−1	91
246	0	−1	−1	−1	4	−1	−1	−1	−1	−1	−1
94	−1	−1	36	−1	−1	0	−1	−1	−1	−1	−1
−1	−1	101	−1	−1	−1	−1	−1	−1	0	−1	22
−1	−1	−1	−1	−1	251	−1	22	0	−1	−1	−1
−1	0	−1	−1	121	−1	−1	−1	−1	−1	194	−1
−1	−1	217	−1	0	−1	159	−1	−1	−1	−1	−1
−1	−1	−1	171	−1	109	−1	−1	−1	−1	−1	0
242	−1	−1	−1	−1	−1	−1	−1	−1	−1	3	0
−1	0	−1	−1	−1	−1	10	−1	−1	−1	−1	212
−1	−1	48	−1	−1	−1	−1	0	−1	140	−1	−1
−1	−1	−1	−1	−1	−1	−1	0	−1	46	43	−1
−1	−1	−1	228	0	−1	−1	−1	−1	−1	153	−1
129	−1	−1	−1	−1	140	−1	−1	−1	−1	−1	0
−1	−1	−1	−1	−1	−1	5	−1	0	58	−1	−1
19	−1	−1	−1	46	−1	−1	−1	0	−1	−1	−1

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
58	0	172	39	242	193	25	120	16	202	207	69
27	−1	42	234	228	241	94	192	0	215	109	88

NOTE – matrix is presented in transposed form to improve readability.

B.1.3 Construction of LDPC(17280, 14592) codeword

The LDPC(17280, 14592) code is a punctured form (see clause B.1.1.1) of the LDPC code matrix of clause B.1.2. The following parameters are used:

– the number of transmitted information bits, $K = 14592$;

– the number of shortened information bits, $S = 0$;

– the number of punctured parity-check bits, $P = 384$;

– the number of parity-check bits after puncturing, $M = 2688$;

– the length of the FEC encoder output, $N = K + M = 17280$;

– the code rate, $R = K / N = 0.8444$.

The LDPC code adopts the LDPC code matrix of clause B.1.2, with 384-bit puncturing and no shortening. The LDPC code matrix is a 12×69 matrix with a circulant size of 256. The payload length is 256×57 bits or 14592 bits, and the parity length is (12×256-384) bits or 2688 bits. The LDPC codeword length is thus 17280 bits. For 49.7664 Gbit/s nominal line rate, this code makes each downstream PHY frame to contain exactly 360 codewords. The LDPC(17280, 14592) has a code rate of 0.844 and supports both hard decision and soft decision implementations.

Annex C

Secure mutual authentication via OMCI

(This annex forms an integral part of this Recommendation.)

This is the same as Annex C of [ITU-T G.987.3].

Annex D

Secure mutual authentication using IEEE 802.1X

(This annex forms an integral part of this Recommendation.)

This is the same as Annex D of [ITU-T G.987.3].

Annex E

(This annex forms an integral part of this Recommendation.)

This annex is intentionally empty.

Annex F

Tuning sequences

(This annex forms an integral part of this Recommendation.)

This is the same as Annex F of [ITU-T G.989.3].

Annex G

Transcoded framing with FEC and OAM for PtP WDM AMCC TC

(This annex forms an integral part of this Recommendation.)

This annex is intentionally empty.

Annex H

Wavelength channel bonding

(This annex forms an integral part of this Recommendation.)

H.1 Bonded ONU activation

An ONU providing wavelength channel bonded services (bonded ONU) supports multiple PON interfaces, each represented by an instance of ANI ME in the single copy of the ONU's OMCI MIB.

A bonded ONU maintains a separate instance of the activation cycle state machine for each associated PON interface. The first PON interface activation should be completed with transition to state O5 before attempting activation on any other PON interface. This PON interface is referred to as pilot PON interface. For pilot PON interface activation, the ONU uses the unassigned ONU-ID (0x03FF) in octets 1-2 of the Serial_Number_ONU PLOAM message. The pilot PON interface is the source of the ONU-ID and the channel partition association.

In response to a serial number grant on each subsequently activated PON interface, the ONU reports the serial number identical to that used for the pilot PON interface activation. In addition, the ONU uses the ONU-ID assigned during the pilot PON interface activation in octets 1-2 of the Serial_Number_ONU PLOAM messages transmitted in all subsequent PON interface activations. The subsequent PON interface activations following the pilot PON interface activation can proceed on a distinct TWDM channel within the channel partition assigned during the pilot interface activation. The subsequent PON interface activations occurring after the pilot PON interface activation can be concurrent.

If the ONU attempts subsequent activation in a channel partition other than the one assigned during the pilot interface activation, or in a TWDM channel in which one PON interface has already been activated, or the ONU reports a serial number different from the one reported during the pilot PON interface activation, or if the OLT CT in a subsequent PON interface activation attempts to assign an ONU-ID different from one used in the course of pilot PON interface activation, the behaviour is undefined.

An OMCC is established for each activated PON interface of a bonded ONU. An OMCI command received on any instance of the OMCC pertains to the same copy of the ONU's OMCI MIB. The ONU responds to an OMCI command on the same PON interface the command was received. The details of OMCC commands serialization and conflict resolution are provided by [ITU-T G.988].

Timing relationships of bonded channels are for future study.

Annex I

Predefined preamble patterns

(This annex forms an integral part of this Recommendation.)

This annex specifies details of predefined preamble patterns which can be used to generate preambles within PSBu segments. A PSBu segment may be based on a predefined preamble pattern, and the chosen preamble pattern may be different for each PSBu segment being part of the same PSBu. Currently included are predefined preamble patterns based on pseudorandom binary sequences (PRBSs), described in clause I.1.

I.1 Predefined preamble patterns based on PRBSs

A PRBS-based preamble pattern of order n=7..15, with a nominal PRBS repetition period of 2^n-1 bits, is padded in order to obtain sequences with a repetition period of 2^n bits. The padding must occur by inserting a single zero bit after 2^n-1 bits of a PRBS, irrespective of the used seed. The preamble is then formed by repeating and/or truncating the resulting 2^n bits to obtain the number of bits requested by the OLT CT, as specified by the preamble word count in the Burst_Profile PLOAM message. The list of generator polynomials used for preambles with a specific PRBS order is listed in Table I.1.

Table I.1 – PRBS generator polynomials for predefined preamble patterns

Preamble pattern codepoint	PRBS order	Generator polynomial	Repetition period after padding [bit]
0111	7	x^7+x^6+1	128
1000	8	$x^8+x^7+x^3+x^2+1$	256
1001	9	x^9+x^5+1	512
1010	10	$x^{10}+x^7+1$	1024
1011	11	$x^{11}+x^9+1$	2048
1100	12	$x^{12}+x^9+x^8+x^5+1$	4096
1101	13	$x^{13}+x^{12}+x^{10}+x^9+1$	8192
1110	14	$x^{14}+x^{13}+x^{11}+x^9+1$	16384
1111	15	$x^{15}+x^{14}+1$	32768

Appendix I

Downstream line data pattern conditioning

(This appendix does not form an integral part of this Recommendation.)

This is the same as Appendix I of [ITU-T G.987.3].

Appendix II

Time of day derivation and error analysis

(This appendix does not form an integral part of this Recommendation.)

This appendix provides the mathematical details for the time of day transfer model derivation and error analysis. It is based on the notation of clause 13.2.1. In addition,

$\boldsymbol{T}_{\mathrm{up}}$ is the upstream propagation delay at the upstream wavelength of PON system,

and

$\boldsymbol{T}_{\mathrm{dn}}$ is the downstream propagation delay at the specific downstream wavelength of PON system.

By constructions (see Figures 13-4 and 13-7 with the accompanying text), the upstream PHY frame offset can be represented using the parameters of ONU$_i$ as:

$$\begin{aligned} Teqd &= T_{dn,i} + RspTime_i + EqD_i + T_{up,i} \\ &= T_{dn,i}\frac{n_{up}+n_{dn}}{n_{dn}} + RspTime_i + EqD_i \end{aligned} \quad \text{(II-1)}$$

Then by expressing $\boldsymbol{T}_{\mathrm{dn,i}}$ from Equation (II-1) as:

$$T_{dn,i} = \left(Teqd - RspTime_i - EqD_i\right)\frac{n_{dn}}{n_{dn}+n_{dn}} \quad \text{(II-2)}$$

substituting this expression into the formula for the receive instance of PHY frame $\boldsymbol{N}$,

$$Trecv_{N,i} = Tsend_{N,i} + T_{dn,i} \quad \text{(II-3)}$$

and regrouping appropriately, then representation of the actual ToD instance when TWDM TC frame $\boldsymbol{N}$ is delivered to ONU$_{\boldsymbol{i}}$ is:

$$Trecv_{N,i} = Tsend_N + Teqd\left[\frac{n_{dn}}{n_{up}+n_{dn}}\right]_{OLT} - \left(EqD_i + RspTime_i\right)\left[\frac{n_{dn}}{n_{up}+n_{dn}}\right]_{ONU} \quad \text{(II-4)}$$

where the positive additive term can be computed by the OLT and communicated downstream, while the negative additive term can be computed by the ONU.

Note that for the model to hold, the measurements of $\boldsymbol{T}$**eqd**, $\boldsymbol{T}$**send**$_{\boldsymbol{N,i}}$ and $\boldsymbol{T}$**recv**$_{\boldsymbol{N,i}}$ should be consistently referenced to the fibre interface at the OLT and ONU, respectively.

Note further that in addition to the ONU response time shown here, there are also internal delays that need to be compensated in both the OLT and ONU. These internal delay compensations directly affect the delivered time accuracy, so the resultant error is quite easy to understand. These errors are not considered further in this treatment.

It should be noted that the refractive index factors are used in calculations on both sides of the PON, and their values could differ depending on the implementation. To eliminate the error caused by inconsistent values, it is recommended that both sides use the common value estimated below.

The resulting timing error caused by variations in the index factor is then given by

$$Terror_{N,i} = Teqd\delta\left[\frac{n_{dn}}{n_{up}+n_{dn}}\right]_{OLT} - \left(EqD_i + RspTime_i\right)\delta\left[\frac{n_{dn}}{n_{up}+n_{dn}}\right]_{ONU} \quad \text{(II-5)}$$

This equation indicates that the error due to the OLT's refractive index factor variation is fixed (over all ONUs), and it is indeed at the maximum value of ***Teqd***, which is typically 250 microseconds. The error due to the ONU's index factor variation depends on the EqD and the response time of that ONU; therefore, nearby ONUs will have a larger error caused by inaccuracies in the ONU's index factor (a rather counter-intuitive result). It should be noted, however, that these errors may cancel out to some degree. To assure this cancelation, it is recommended that the calculation use the common value estimated below.

Assessing the index factor, one can denote the group refractive index at downstream wavelength with ***n*** and the difference between group indices at upstream wavelength and downstream wavelength with **Δ*n***, rewriting

$$\frac{n_{dn}}{n_{up}+n_{dn}}=\frac{n_{dn}}{2n_{dn}+(n_{up}-n_{dn})}=\frac{n}{2n+\Delta n}\approx\frac{2n^2-n\Delta n}{4n^2}=\frac{1}{2}-\frac{\Delta n}{4n} \qquad \text{(II-6)}$$

Variations of ***n*** and **Δ*n*** effect can be realized by taking partial derivatives with respect to these variables. It can be seen that

$$\frac{\partial}{\partial n}\left(\frac{1}{2}-\frac{\Delta n}{4n}\right)=+\frac{\Delta n}{4n^2}\ \text{and}\ \frac{\partial}{\partial \Delta n}\left(\frac{1}{2}-\frac{\Delta n}{4n}\right)=-\frac{1}{4n} \qquad \text{(II-7)}$$

It is important to note that ***n*** is about three orders of magnitude larger than **Δ*n***. Therefore, the first expression is very much smaller than the second one, and can be neglected. The second expression states that small changes in **Δ*n*** will be translated into small changes of the index factor in the proportion 1/4***n***.

So, it is essential to calculate **Δ*n*** (the "index difference"), and then consider its variations.

Calculation of the index difference

The wavelength-dependent difference in refractive index Δ***n*** depends on the fibre properties and on the actual wavelengths that are involved (as real PON transmitters may operate over a range of wavelengths). An accurate representation of the index of [b-ITU-T G.652] fibre is difficult to obtain. Typical spot values for the index at 1310 and 1550 nm are available, but these do not have the accuracy that is needed. The dispersion of fibres is given for certain windows (the 1310 window, for example), but these formulations are not really accurate when extrapolated beyond their window. Nevertheless, it is desired to proceed with the standardized dispersion factor, despite the potential inaccuracy that such a generalization imposes. If a better function can be determined, then the analysis can be applied to that.

The dispersion of [b-ITU-T G.652] fibre is given by

$$D(\lambda)=\frac{\lambda S_0}{4}\left[1-\frac{\lambda_0^4}{\lambda^4}\right] \qquad \text{(II-8)}$$

where $\boldsymbol{S_0}$ is the dispersion slope (maximum 0.092 ps/nm^2/km), and λ_0 is the zero dispersion wavelength (ranging from 1300 to 1324 nm).

The index of refraction and ***D*** are related by $\frac{dn}{d\lambda}=cD(\lambda)$, and the fundamental theorem of calculus implies that:

$$n=n_0+c\int_{\lambda_0}^{\lambda}D(\lambda)d\lambda \qquad \text{(II-9)}$$

Integrating, it indicates that:

$$n - n_0 = \frac{cS_0}{8}\lambda^2\left[1-\frac{\lambda_0^2}{\lambda^2}\right]^2 \quad \text{(II-10)}$$

The index difference function is graphed in Figure II.1 for the two extreme cases of [b-ITU-T G.652] fibre, where the zero dispersion wavelengths are 1300 and 1324 nm

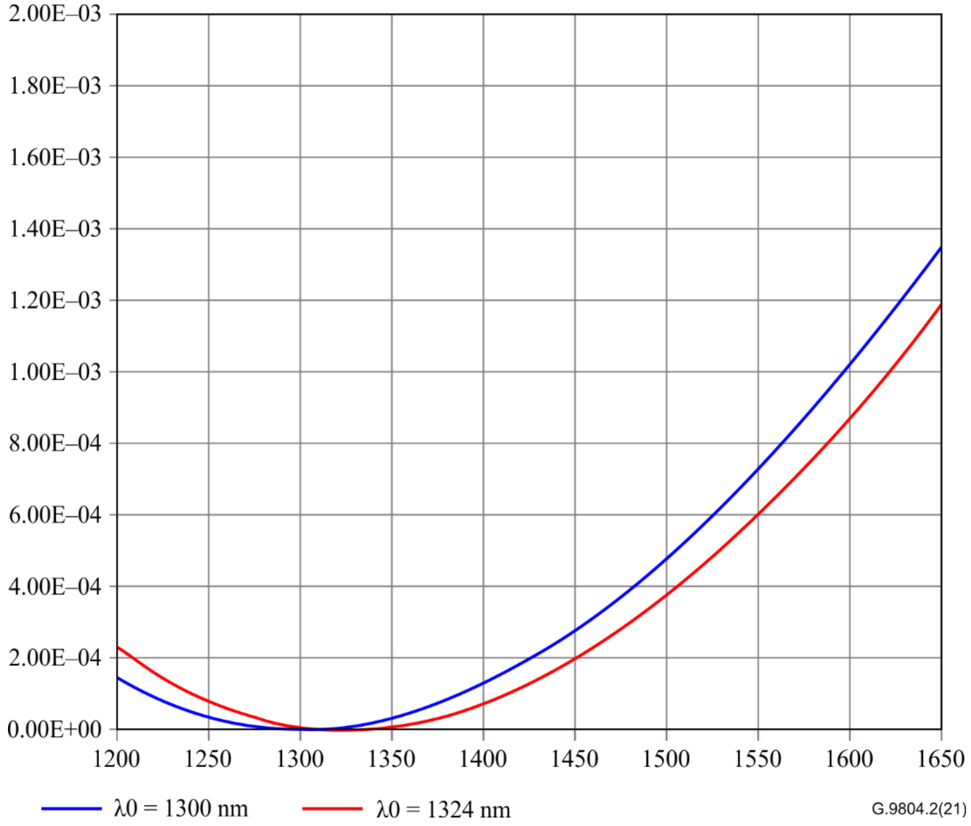


Figure II.1 – Refractive index difference as a function of operating wavelength

In practical systems, operating wavelengths are not monitored, nor is the exact fibre dispersion known. Hence, the index difference is truly an unknown quantity.

Appendix III

Burst profiles

(This appendix does not form an integral part of this Recommendation.)

This appendix describes burst profiles to be used by the PHY adaptation sublayer of the ONU to form the PHY burst. Suggested PSBu configurations for 12.5 Gbit/s are presented.

In the HSP system, upstream transmission from ONUs to the OLT CT is conducted by delivering a number of PHY bursts. After a two-time-quanta guard time for burst overlap prevention, the PHY burst starts with the upstream physical synchronization block (PSBu) section. Time quantum is defined in clause 3.2.3. The PSBu is composed of one to four PSBu segments, each containing a separate preamble and delimiter. PSBu is employed by the OLT CT burst mode receiver to determine the presence of a PHY burst and delineate the PHY burst. They are also used to determine the signal clock and/or equalizer taps in order to correctly recover the transmitted signal.

The specific burst profile to be used by an ONU is indicated by the OLT in the BurstProfile field of the BWmap. The index in the BurstProfile field refers to the set of valid burst profiles that is communicated to the ONUs over the PLOAM messaging channel. For each specified profile, the index is explicitly assigned in the Burst _Profile PLOAM message.

The Burst_Profile PLOAM message can be broadcast or unicast. It is up to the OLT CT to manage the burst profiles, and to anticipate which ONUs will have which profiles. The ONU will transmit a burst profile as specified by the OLT CT. In the simplest case, the OLT CT can send only broadcast profile messages. The profiles then obtain global scope, and are equal on all ONUs within a channel. In a more complex case, the OLT CT can send unicast profiles to each ONU. These unicast profiles could then be different for each ONU (again, it is incumbent on the OLT CT to keep track of what it has configured in each ONU). Regarding temporal behaviour, the OLT CT should always send the profile message several times before it attempts to use them in a BWmap. In this way, the probability of the ONU using an old profile will be greatly reduced.

PSBu may be composed of one up to four segments, where each segment contains an individual preamble pattern and delimiter in order to assist upstream signal acquisition functions in HSP. The recommended length of PSBu is specified in the applicable PMD Recommendations. Preambles with varying sizes can be achieved by setting the burst profile to the desired configuration.

A traditional PSBu is composed of one segment with a preamble pattern 0x AAAA AAAA. While it provides maximum transition density and DC balance, some implementations may have different PSBu requirements. For example, if the burst mode receiver has bandwidth limited frontends, the aforementioned preamble pattern is not able to support equalizer convergence and subsequent burst. delineation and data recovery may fail. Another example is burst mode receivers with peak detectors. If the peak detectors have limited slew rates in the sample and hold circuit, the aforementioned preamble may not allow for burst presence detection. Therefore, predefined preamble patterns may be selected as possible preamble patterns. The selected predefined preamble patterns based on pseudorandom binary sequences (PRBS) are expected to have features of DC balance, flat power spectrum, transition density similar to that of random data and long repetition period. The discussion on the recommended seeds used to generate PRBS-based preambles is contained in clause III.1.

Delimiters terminate each PSBu segment and their length can be set to zero bits. The delimiter associated with the last transmitted PSBu segment (final delimiter) is used to delineate the PHY burst payload carrying the upstream FS burst. Its non-zero-length is effectively mandatory in a practical system. The recommended length of the final delimiter is 64 bits. A shorter final delimiter of 32 bits is also allowed. The delimiter lengths are configurable via the Burst_Profile PLOAM message. Delimiters terminating PSBu segments may be used to indicate transitions between PSBu segments if required by the OLT CT optical receiver implementation. The expected features of the selected delimiters include DC balance, and large Hamming distance from all shifted patterns of each delimiter and preamble pattern being part of the same PSBu. Some examples of 32- and 64-bit delimiters are included in clause III.2.

III.1 Recommended seeds for preambles based on PRBSs

Although in principle any seed (except for all-zero seed), can be specified in the Burst_Profile PLOAM message, only some of the seeds will guarantee that within a single repetition period of the generated sequence of length 2^n, the number of occurrences of all possible substrings of length m, where $0<m\leq n$ will be uniform. Such sequences are called De Bruijn sequences $B(2,n)$, where 2 represents a binary alphabet, and are the shortest sequences where every substring of n bits occurs exactly once (as opposed to PRBS, also called maximum-length sequence, where an n-bit substring of zeros does not occur). Equal probability of each substring of m bits within one repetition period of the 2^n-bit-long sequence may be beneficial for certain types of equalizers which rely on statistical approaches, requiring e.g., estimation of state transition probabilities. In order to convert a PRBS of order n (PRBS(n)) into a $B(2,n)$ sequence, it is sufficient to insert a zero at a position, which extends the longest run of zeros (equal to $n-1$ consecutive zeros) in PRBS(n) into a run of n consecutive zeros. Given that for practical reasons the insertion of zero is defined to occur at a final position after each PRBS repetition, as specified in Annex I.1, it is possible to find seeds which result in PRBS patterns that after insertion of the final zero become De Bruijn sequences. The rule is that the longest run of $n-1$ zeros of the generated PRBS is adjacent to, or broken across, the 2^n-1 bit boundary. Yet another benefit of De Bruijn sequences is that they partly preserve some of the synchronization properties of PRBS, specifically, the ability to initialize the receiver's sequence generator with any n bits, as long as they are not all zeros. Synchronization property may be needed for equalizer implementations requiring a reference signal, and would not be possible if the padding zero is present in an arbitrary position of the preamble pattern (although the padding zero is always inserted in the final preamble pattern position, specifying a different seed is equivalent to a circular shift of the preamble pattern, which in turn causes the padding zero to appear as inserted at an arbitrary position in the preamble pattern, thus breaking the synchronization property as a result).

In Table III.1 we list all possible n seeds for each PRBS(n), which result in conversion to De Bruijn sequence $B(2,n)$ after insertion of the single padding zero in the final position.

The most significant non-zero bit of the seed value is the state of the highest order tap x^n required to generate PRBS(n), which is also the output of the linear feedback shift register. The least significant bit (LSB) is the state of the leftmost register position (associated with the first tap x^1 and connected to the feedback), which will shift to the highest order tap x^n (output) after $n-1$ clock cycles. The seeds are given in the order where the first seed in each row results in a sequence starting with $n-1$ zeros followed by one, and the generation is subsequently delayed by one bit for each next seed in the list, until the last seed, which contains the run of $n-1$ zeros at the end of the repetition period.

Table III.1 – Recommended seeds

PRBS order	Seeds in hexadecimal (LSB = tap x^1)
7	0001, 0002, 0004, 0008, 0010, 0020, 0041
8	0001, 0002, 0005, 000B, 0017, 002E, 005C, 00B8
9	0001, 0002, 0004, 0008, 0010, 0021, 0042, 0084, 0108
10	0001, 0002, 0004, 0008, 0010, 0020, 0040, 0081, 0102, 0204
11	0001, 0002, 0004, 0008, 0010, 0020, 0040, 0080, 0100, 0201, 0402
12	0001, 0002, 0004, 0008, 0010, 0021, 0042, 0084, 0109, 0213, 0427, 084E

Table III.1 – Recommended seeds

PRBS order	Seeds in hexadecimal (LSB = tap x^1)
13	0001, 0002, 0004, 0008, 0010, 0020, 0040, 0080, 0100, 0201, 0403, 0806, 100D
14	0001, 0002, 0004, 0008, 0010, 0020, 0040, 0080, 0100, 0201, 0402, 0805, 100A, 2015
15	0001, 0002, 0004, 0008, 0010, 0020, 0040, 0080, 0100, 0200, 0400, 0800, 1000, 2000, 4001

III.2 Recommended PSBu structure for 12.5 Gbit/s upstream rate

Since use of FEC at 12.5 Gbit/s upstream rate is configurable, it may be desirable to indicate if the burst has FEC active or not using a pair of distinct delimiters. The suggested values of preamble pattern and delimiter pairs for a PSBu containing a single PSBu segment are shown in Table III.2.

Table III.2 – Suggested values of a preamble pattern and delimiter of a single-segment PSBu for 12.5 Gbit/s upstream rate

Preamble pattern	FEC indication	32-bit delimiter	64-bit delimiter
0x BB52 1E26	–	0x A376 70C9	0x B9D4 3E68 462B C197
	On	0x 4BDE 1B90	0x B9D4 3E68 462B C197
	Off	0x A376 70C9	0x B752 1F06 48AD E879
0x AAAA AAAA	–	0x AD4C C30F	0x B3BD D310 B2C5 0FA1
	On	0x A566 79E0	0x B3BD D310 B2C5 0FA1
	Off	0x AD4C C30F	0x CE99 CE5E 5028 B41F

Appendix IV

Golden vectors

(This appendix does not form an integral part of this Recommendation.)

Golden vectors of AES-128 encryption, key derivation encryption, PLOAM message integrity check, upstream key reporting, and OMCI message integrity are the same as Appendix IV of [ITU-T G.989.3].

IV.1 50G downstream FEC codeword

This is an example of a FEC codeword for downstream at a nominal line rate of 49.7664 Gbit/s. The payload is an incrementing string of words starting at 0x0001 and having the length of 1824 bytes (14592 bits). The 336 FEC parity bytes (2688 bits) are shown underlined.

LDPC(17280, 14592)

```
0001_0002_0003_0004_0005_0006_0007_0008_0009_000a_000b_000c_000d_000e_000f_0010
0011_0012_0013_0014_0015_0016_0017_0018_0019_001a_001b_001c_001d_001e_001f_0020
0021_0022_0023_0024_0025_0026_0027_0028_0029_002a_002b_002c_002d_002e_002f_0030
0031_0032_0033_0034_0035_0036_0037_0038_0039_003a_003b_003c_003d_003e_003f_0040
0041_0042_0043_0044_0045_0046_0047_0048_0049_004a_004b_004c_004d_004e_004f_0050
0051_0052_0053_0054_0055_0056_0057_0058_0059_005a_005b_005c_005d_005e_005f_0060
0061_0062_0063_0064_0065_0066_0067_0068_0069_006a_006b_006c_006d_006e_006f_0070
0071_0072_0073_0074_0075_0076_0077_0078_0079_007a_007b_007c_007d_007e_007f_0080
0081_0082_0083_0084_0085_0086_0087_0088_0089_008a_008b_008c_008d_008e_008f_0090
0091_0092_0093_0094_0095_0096_0097_0098_0099_009a_009b_009c_009d_009e_009f_00a0
00a1_00a2_00a3_00a4_00a5_00a6_00a7_00a8_00a9_00aa_00ab_00ac_00ad_00ae_00af_00b0
00b1_00b2_00b3_00b4_00b5_00b6_00b7_00b8_00b9_00ba_00bb_00bc_00bd_00be_00bf_00c0
00c1_00c2_00c3_00c4_00c5_00c6_00c7_00c8_00c9_00ca_00cb_00cc_00cd_00ce_00cf_00d0
00d1_00d2_00d3_00d4_00d5_00d6_00d7_00d8_00d9_00da_00db_00dc_00dd_00de_00df_00e0
00e1_00e2_00e3_00e4_00e5_00e6_00e7_00e8_00e9_00ea_00eb_00ec_00ed_00ee_00ef_00f0
00f1_00f2_00f3_00f4_00f5_00f6_00f7_00f8_00f9_00fa_00fb_00fc_00fd_00fe_00ff_0100
0101_0102_0103_0104_0105_0106_0107_0108_0109_010a_010b_010c_010d_010e_010f_0110
0111_0112_0113_0114_0115_0116_0117_0118_0119_011a_011b_011c_011d_011e_011f_0120
0121_0122_0123_0124_0125_0126_0127_0128_0129_012a_012b_012c_012d_012e_012f_0130
0131_0132_0133_0134_0135_0136_0137_0138_0139_013a_013b_013c_013d_013e_013f_0140
0141_0142_0143_0144_0145_0146_0147_0148_0149_014a_014b_014c_014d_014e_014f_0150
0151_0152_0153_0154_0155_0156_0157_0158_0159_015a_015b_015c_015d_015e_015f_0160
0161_0162_0163_0164_0165_0166_0167_0168_0169_016a_016b_016c_016d_016e_016f_0170
0171_0172_0173_0174_0175_0176_0177_0178_0179_017a_017b_017c_017d_017e_017f_0180
0181_0182_0183_0184_0185_0186_0187_0188_0189_018a_018b_018c_018d_018e_018f_0190
0191_0192_0193_0194_0195_0196_0197_0198_0199_019a_019b_019c_019d_019e_019f_01a0
01a1_01a2_01a3_01a4_01a5_01a6_01a7_01a8_01a9_01aa_01ab_01ac_01ad_01ae_01af_01b0
01b1_01b2_01b3_01b4_01b5_01b6_01b7_01b8_01b9_01ba_01bb_01bc_01bd_01be_01bf_01c0
01c1_01c2_01c3_01c4_01c5_01c6_01c7_01c8_01c9_01ca_01cb_01cc_01cd_01ce_01cf_01d0
01d1_01d2_01d3_01d4_01d5_01d6_01d7_01d8_01d9_01da_01db_01dc_01dd_01de_01df_01e0
01e1_01e2_01e3_01e4_01e5_01e6_01e7_01e8_01e9_01ea_01eb_01ec_01ed_01ee_01ef_01f0
01f1_01f2_01f3_01f4_01f5_01f6_01f7_01f8_01f9_01fa_01fb_01fc_01fd_01fe_01ff_0200
0201_0202_0203_0204_0205_0206_0207_0208_0209_020a_020b_020c_020d_020e_020f_0210
0211_0212_0213_0214_0215_0216_0217_0218_0219_021a_021b_021c_021d_021e_021f_0220
0221_0222_0223_0224_0225_0226_0227_0228_0229_022a_022b_022c_022d_022e_022f_0230
0231_0232_0233_0234_0235_0236_0237_0238_0239_023a_023b_023c_023d_023e_023f_0240
0241_0242_0243_0244_0245_0246_0247_0248_0249_024a_024b_024c_024d_024e_024f_0250
0251_0252_0253_0254_0255_0256_0257_0258_0259_025a_025b_025c_025d_025e_025f_0260
0261_0262_0263_0264_0265_0266_0267_0268_0269_026a_026b_026c_026d_026e_026f_0270
0271_0272_0273_0274_0275_0276_0277_0278_0279_027a_027b_027c_027d_027e_027f_0280
0281_0282_0283_0284_0285_0286_0287_0288_0289_028a_028b_028c_028d_028e_028f_0290
0291_0292_0293_0294_0295_0296_0297_0298_0299_029a_029b_029c_029d_029e_029f_02a0
02a1_02a2_02a3_02a4_02a5_02a6_02a7_02a8_02a9_02aa_02ab_02ac_02ad_02ae_02af_02b0
02b1_02b2_02b3_02b4_02b5_02b6_02b7_02b8_02b9_02ba_02bb_02bc_02bd_02be_02bf_02c0
02c1_02c2_02c3_02c4_02c5_02c6_02c7_02c8_02c9_02ca_02cb_02cc_02cd_02ce_02cf_02d0
02d1_02d2_02d3_02d4_02d5_02d6_02d7_02d8_02d9_02da_02db_02dc_02dd_02de_02df_02e0
02e1_02e2_02e3_02e4_02e5_02e6_02e7_02e8_02e9_02ea_02eb_02ec_02ed_02ee_02ef_02f0
02f1_02f2_02f3_02f4_02f5_02f6_02f7_02f8_02f9_02fa_02fb_02fc_02fd_02fe_02ff_0300
0301_0302_0303_0304_0305_0306_0307_0308_0309_030a_030b_030c_030d_030e_030f_0310
```

```
0311_0312_0313_0314_0315_0316_0317_0318_0319_031a_031b_031c_031d_031e_031f_0320
0321_0322_0323_0324_0325_0326_0327_0328_0329_032a_032b_032c_032d_032e_032f_0330
0331_0332_0333_0334_0335_0336_0337_0338_0339_033a_033b_033c_033d_033e_033f_0340
0341_0342_0343_0344_0345_0346_0347_0348_0349_034a_034b_034c_034d_034e_034f_0350
0351_0352_0353_0354_0355_0356_0357_0358_0359_035a_035b_035c_035d_035e_035f_0360
0361_0362_0363_0364_0365_0366_0367_0368_0369_036a_036b_036c_036d_036e_036f_0370
0371_0372_0373_0374_0375_0376_0377_0378_0379_037a_037b_037c_037d_037e_037f_0380
0381_0382_0383_0384_0385_0386_0387_0388_0389_038a_038b_038c_038d_038e_038f_0390
2cb9 9d71 4de4 7d13 dffe dd5f 8a68 15db e60b 0ecd 0447 37b0 4de8 65d7 a981 a221
c91b a7c4 a843 be13 656e 6ac0 9d01 6204 16a9 7520 d8b1 9e53 3b78 e441 3975 236a
4350 dfd6 1eb4 3fa1 4809 86e8 42ef 2088 4b75 6b2a 73aa fb1f 978e 8e08 1e98 c0c8
d511 9aaf 9575 5365 206c 3b55 b6e3 9361 5fe7 16e9 0419 d25f 1298 8754 2393 bc0f
583e 73bd 3093 a93a fd18 946e 9fec fc35 533c 82df 2be8 381b f7d8 5fd4 1ce8 75d9
5628 2662 b707 41c5 f9b0 1a3f e9c4 c25f 6a65 0059 628f 1b00 d2f4 303a ddaf 30ee
7813 b913 2a06 0249 9779 109c e30f ad53 8ed6 d6ca b330 ae1a c4c9 1d53 92f7 f6f9
d5c6 9735 d319 fbdd 2166 15be 22db f52d 8594 8604 a9bc 3131 1542 4231 6dd1 671f
813a d491 506e 6684 074a d123 9b78 2232 dd51 6ab1 6687 20e0 a6f8 e47f f6f1 58bc
ea50 2f3e a42b 7c1b c4be c411 d139 e673 b156 85fc 09c7 9344 3c56 da67 6b1d 2206
d6e1 995f 9685 5095 239c 38a5 b513 9091
```

IV.2 PSBu segment preamble based on PRBSs

The following golden vectors for each combination of a PRBS order and seed specify the first 256 bits as they are to be transmitted on the optical channel, assuming a preamble with at least 256 bits is to be generated. The most significant bit (MSB) is transmitted first. These vectors may be used to verify correct operation of the PRBS-based preamble generator. The seeds are chosen so that the first *n* bits transmitted on the optical channel are the first *n* most significant bits of a characteristic binary sequence 1010 1100 1110 0010. In general, the first *n* bits of the sequence on the optical channel shall always correspond to *n* rightmost bits of the PRBS seed specified in octets 20-21 of the Burst_Profile PLOAM message.

Table IV.1 – PRBS-based preamble segment golden vectors

PRBS order	**Seed in hexadecimal** (LSB = tap x^1)	**First 256 bits transmitted on the optical channel in hexadecimal** (MSB = transmitted first)
7	0056	AD EC 69 77 32 AF E0 41 85 1E 45 9D 4F A1 C4 9A AD EC 69 77 32 AF E0 41 85 1E 45 9D 4F A1 C4 9A
8	00AC	AC 60 96 D4 D3 F7 33 D9 08 1C 93 13 AB 44 52 3E 02 E3 BC 59 B0 F3 85 7F 97 A5 0D DB EB A0 CA A2
9	0159	AC B3 C7 DD 06 B6 EC 16 BE AA 05 2B CB B8 1C E9 3D 75 12 19 C2 F6 CD 0E F0 FF 83 DF 17 32 09 4E
10	02B3	AC F2 D9 04 49 81 62 9D 9C 5F A8 BB 58 66 D4 1D 3D 35 27 07 CE 6F 45 5B E1 3A 3A FB 48 42 95 8E
11	0567	AC E3 ED 8B 74 D4 F0 E6 6F FA 02 41 68 99 5F 84 32 9F 1C 6D BB 6A D8 37 1D 6D 1B 2E F2 A7 07 63
12	0ACE	AC E7 61 AA 34 2C 18 15 37 45 BE CC 27 C8 10 19 DA 79 2B 77 C5 70 1F EE 93 AE 32 5A 86 5F EA B4
13	159C	AC E2 E0 F1 4C 6B 8A C3 2B 74 8B 8B C3 F3 25 F0 F4 CF BE B6 E8 17 CF D6 9D 34 ED A4 0C 65 8E D0
14	2B38	AC E0 38 9A 78 C9 58 E8 CD 9A 24 EF 5E 83 1F F8 83 77 C3 78 C5 5F 3B FF B0 2D 52 DC E8 7D D3 4A
15	5671	AC E3 EA 48 7D B1 0D A6 2D D4 EC FA 6A 1D 7C 4F 09 A2 35 CC BC AB 8B F9 38 16 90 77 61 33 46 AB

Appendix V

Protection examples

(This appendix does not form an integral part of this Recommendation.)

This appendix is intentionally empty.

Appendix VI

ICTP: Inter-channel-termination protocol

(This appendix does not form an integral part of this Recommendation.)

This is the same as Appendix VI of [ITU-T G.989.3].

Appendix VII

ONU equalization delay coordination across TWDM channels

(This appendix does not form an integral part of this Recommendation.)

This is the same as Appendix VII of [ITU-T G.989.3].

Appendix VIII

PON-ID and system identifier examples

(This appendix does not form an integral part of this Recommendation.)

This is the same as Appendix VIII of [ITU-T G.989.3].

Appendix IX

Quiet window elimination in ONU activation

(This appendix does not form an integral part of this Recommendation.)

A dedicated activation wavelength (DAW, λ_{DA}) is introduced to eliminate quiet window during activation. There are three scenarios about how DAW is applied and how activation works.

IX.1 Scenario A: new dedicated activation wavelength (λ_{DA})

In this scenario, as shown in Figure IX.1, 50G-PON contains three wavelengths:

– λ_{50Gd}: Downstream wavelength of 50G-PON

– λ_{50Gu}: Upstream wavelength of 50G-PON

– λ_{DA}: Dedicated activation wavelength in the upstream

Activation process for this scenario (basic activation) is shown as:

1) Upon power on, ONU works at λ_{50Gd} and λ_{DA}, listens SN request at λ_{50Gd}.
2) OLT opens quiet window at λ_{DA} and broadcasts the Serial Number (SN) request at λ_{50Gd}.
3) ONU responds with its SN at λ_{DA} after receiving the Serial Number (SN) request at λ_{50Gd}.
4) Once OLT receives the SN from ONU, it opens quiet window at λ_{DA} and sends ranging request at λ_{50Gd} directly to the ONU.
5) The ONU responds with ranging response at λ_{DA} after receiving the ranging request at λ_{50Gd}.
6) After receiving the ranging response, OLT calculates the ranging results at $\lambda_{50Gd}/\lambda_{DA}$ based on timing relationship between transmission of the ranging request and reception of the ranging response. OLT further calculates the ranging results at $\lambda_{50Gd}/\lambda_{50Gu}$ using the ranging results at $\lambda_{50Gd}/\lambda_{DA}$ based on the dispersion difference between λ_{50Gu} and λ_{DA}. OLT sends the ranging results at $\lambda_{50Gd}/\lambda_{50Gu}$ to the ONU.
7) The ONU applies the ranging result at $\lambda_{50Gd}/\lambda_{50Gu}$ and starts working on λ_{50Gu} (including tuning from λ_{DA} to λ_{50Gu} in case of tunable ONUs, or switching from λ_{DA} to λ_{50Gu} in case of dual-wavelengths ONUs).
8) OLT assigns a directed upstream bandwidth with burst profile of long preamble to the newly activated ONU at λ_{50Gd}.
9) ONU responses Acknowledgement PLOAMu message to OLT.
10) OLT assigns a directed upstream bandwidth with burst profile of short preamble to the ONU at λ_{50Gd}.
11) ONU enters the operational state.

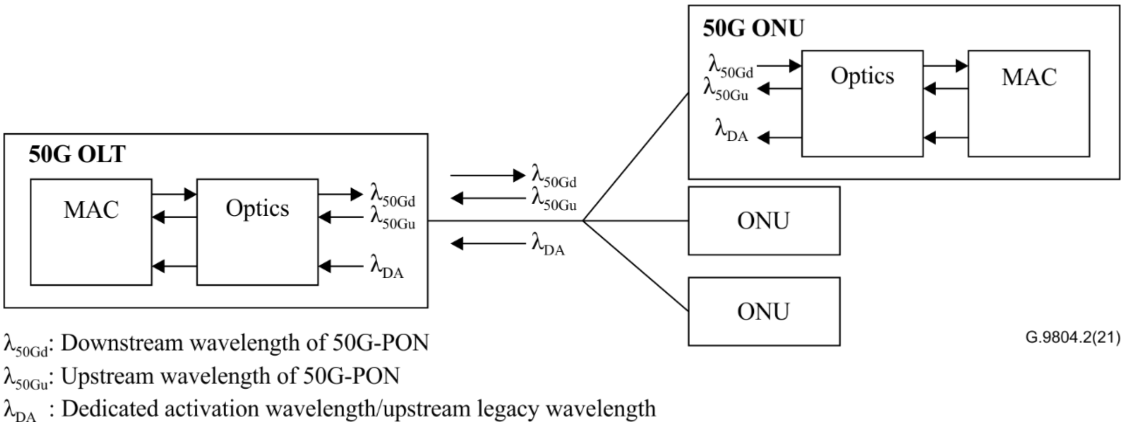


Figure IX.1 – Scenario A with newly defined λ_{DA}

IX.2 Scenario B: legacy dedicated activation wavelength (λ_{DA})

In this scenario, 50G-PON, together with legacy PON, contains four wavelengths:

– λ_{50Gd}: Downstream wavelength of 50G-PON;

– λ_{50Gu}: Upstream wavelength of 50G-PON;

– λ_{DA}: legacy upstream wavelength used as the dedicated activation wavelength in the upstream;

– λ_{Ld}: legacy downstream wavelength.

In this scenario, there should be coordination between 50G OLT and legacy OLT during activation or quiet window opening. Depending on reception of signals at λ_{DA}, this scenario is further separated into scenarios B1, B2 and B3, as shown in Figures IX.2, IX.3 and IX.4, respectively.

IX.2.1 Scenario B1

In scenario B1, as shown in Figure IX.2, legacy MAC is integrated with 50G MAC in the OLT. The coordination between legacy MAC and 50G MAC is a local process. The activation process is the same as the activation in scenario A.

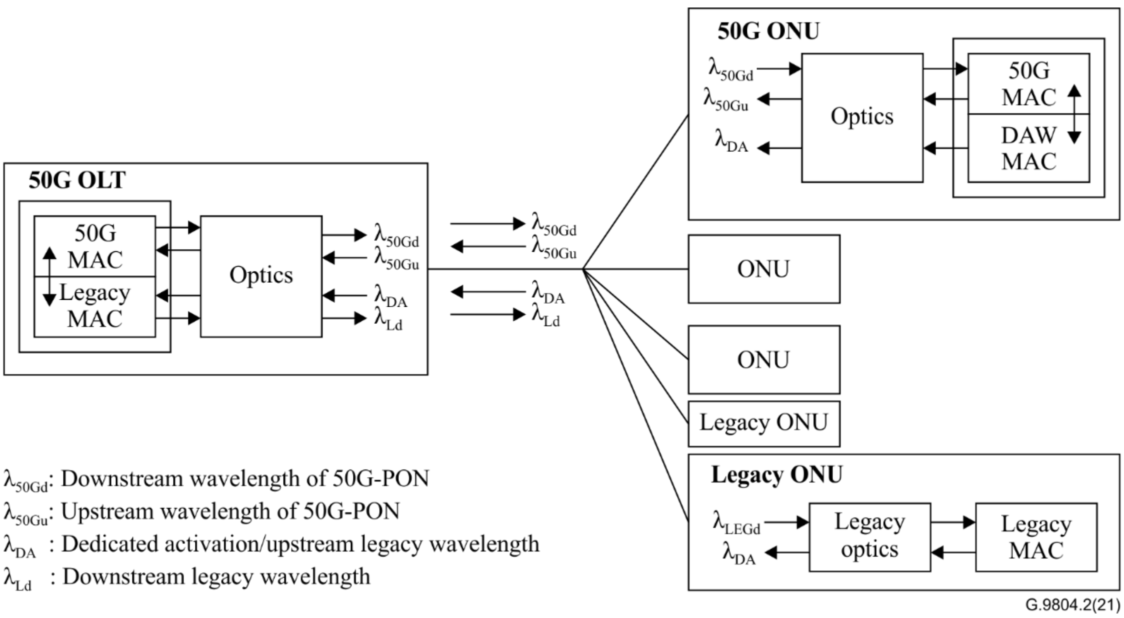


Figure IX.2 – Scenario B1 with integrated legacy upstream wavelength as λ_{DA}

IX.2.2 Scenario B2

In scenario B2 as shown in Figure IX.3, legacy OLT is independent from 50G OLT. λ_{DA} is sent to both 50G OLT and legacy OLT. A 2:1 splitter is connected from trunk fibre to 50G OLT and legacy OLT. Both 50G OLT and legacy OLT open quiet windows on λ_{DA}. They should coordinate opening quiet window. The activation process works as below:

1) Upon power on, ONU works at λ_{50Gd} and λ_{DA}.

2) OLT coordinates with legacy OLT to open quiet window at λ_{DA} and broadcasts Serial Number (SN) request at λ_{50Gd}.

   (NOTE – this step is different from step 2 of the process in scenario A).

3) ONU responds with its SN at λ_{DA} after receiving the Serial Number (SN) request at λ_{50Gd}.

4) Once OLT receives SN from ONU, it opens quiet window at λ_{DA} and sends the ranging request at λ_{50Gd} directly to the ONU.

5) The ONU responds with ranging response at λ_{DA} after receiving the ranging request at λ_{50Gd}.

6) After receiving ranging response, OLT calculates ranging results at $\lambda_{50Gd}/\lambda_{DA}$ based on timing relationship. OLT then calculates ranging results at $\lambda_{50Gd}/\lambda_{50Gu}$ based on dispersion difference between λ_{50Gu} and λ_{DA}. OLT sends ranging results at $\lambda_{50Gd}/\lambda_{50Gu}$ to the ONU.

7) The ONU applies the ranging result at $\lambda_{50Gd}/\lambda_{50Gu}$ and starts working on λ_{50Gu} (including tuning from λ_{DA} to λ_{50Gu} when tunable, or switching from λ_{DA} to λ_{50Gu} when dual wavelengths).

8) OLT assigns a directed upstream bandwidth with burst profile of long preamble to the newly activated ONU at λ_{50Gd}.

9) ONU responses Acknowledgement PLOAMu message to OLT.

10) OLT assigns a directed upstream bandwidth with burst profile of short preamble to the ONU at λ_{50Gd}.

11) ONU enters the operational state.

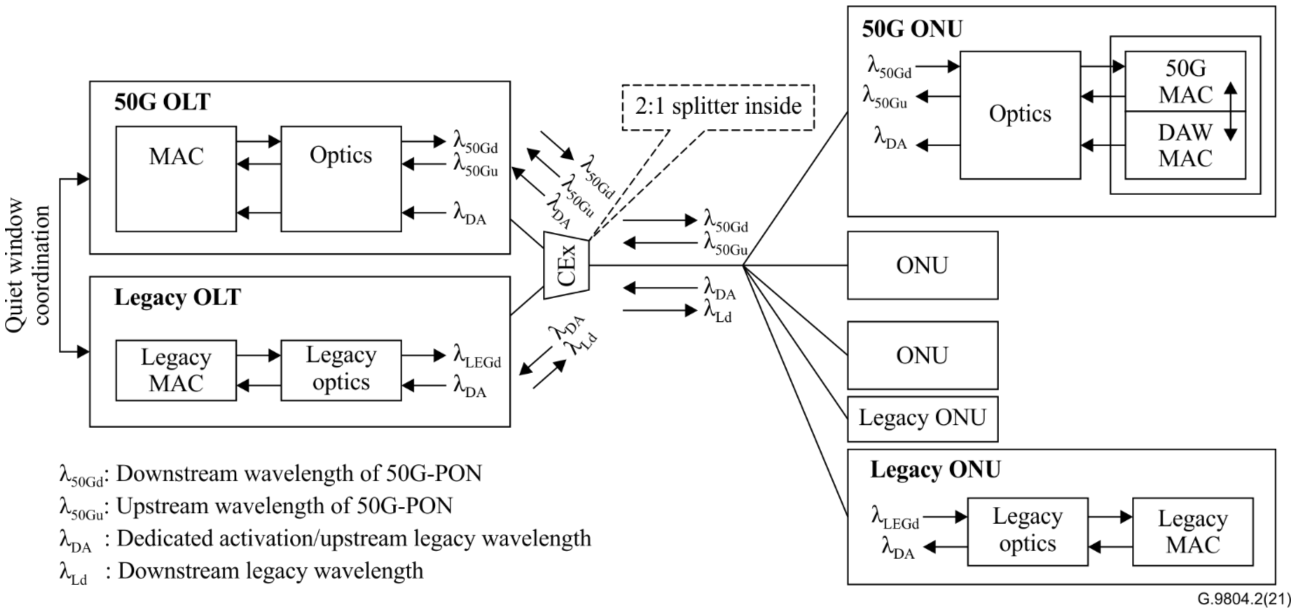


Figure IX.3 – Scenario B2 with independent legacy upstream wavelength as DAW connected to both 50G OLT and legacy OLT

IX.2.3 Scenario B3

In scenario B3, as shown in Figure IX.4, legacy OLT is independent from 50G OLT. λ_{DA} is sent to only legacy OLT. Both 50G OLT and legacy OLT coordinate with each other to open the quiet windows on λ_{DA}. Furthermore, legacy OLT receives SN response and ranging response, and then forwards them to 50G OLT. The activation process works as below:

1) Upon power on, ONU works at λ_{50Gd} and λ_{DA}.

2) The 50G OLT coordinates with legacy OLT to open quiet window at λ_{DA} and broadcasts Serial Number (SN) request at λ_{50Gd}.

   (NOTE – this step is different from step 2 of the process in scenario A).

3) ONU responds with its SN at λ_{DA} after receiving the Serial Number (SN) request at λ_{50Gd}.

4) Once OLT receives SN from ONU, which is forwarded from legacy OLT, it opens a quiet window at λ_{DA} and sends ranging request at λ_{50Gd} directly to the ONU.

5) The ONU responds with ranging response at λ_{DA} after receiving the ranging request at λ_{50Gd}.

6) After receiving the ranging response, which is forwarded from legacy OLT, OLT calculates ranging results at $\lambda_{50Gd}/\lambda_{DA}$ based on timing relationship and further calculates ranging results at $\lambda_{50Gd}/\lambda_{50Gu}$ based on dispersion difference between λ_{50Gu} and λ_{DA}. OLT sends ranging results at $\lambda_{50Gd}/\lambda_{50Gu}$ to the ONU.

7) The ONU applies the ranging result at $\lambda_{50Gd}/\lambda_{50Gu}$ and starts working on λ_{50Gu} (including tuning from λ_{DA} to λ_{50Gu} if the ONU is tunable, or switching from λ_{DA} to λ_{50Gu} if it's a dual-wavelength ONU).

8) OLT assigns a directed upstream bandwidth with burst profile of long preamble to the newly activated ONU at λ_{50Gd}.

9) ONU responses Acknowledgement PLOAMu message to OLT.

10) OLT assigns a directed upstream bandwidth with burst profile of short preamble to the ONU at λ_{50Gd}.

11) ONU enters the operational state.

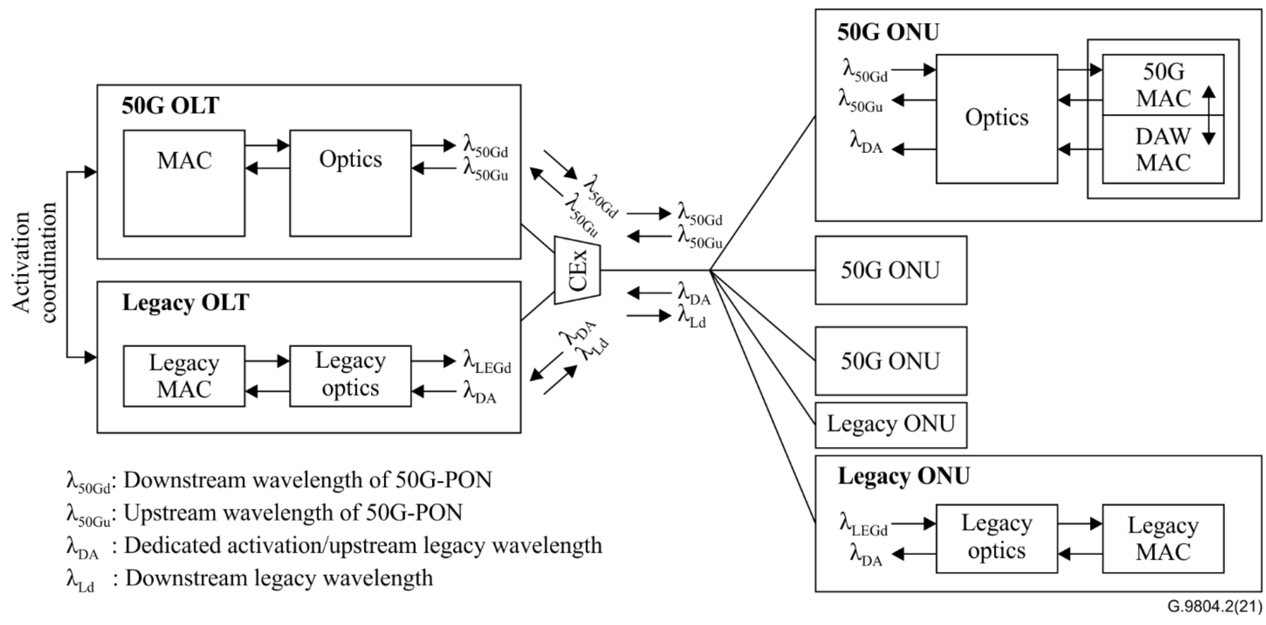


Figure IX.4 – Scenario B3 with independent legacy upstream wavelength as DAW connected to only legacy OLT

IX.3 Scenario C: legacy dedicated activation wavelength (λ_{DA})

The DAW ONU is separated from 50G ONU. This scenario requires the 50G OLT to know the relationship between a 50G ONU and the corresponding DAW ONU. For example, a 50G ONU and the corresponding DAW ONU are set from one user by paring their SNs. Then 50G OLT can use the activation information of a DAW ONU to the corresponding 50G ONU. DAW ONU activates with legacy OLT just like a legacy ONU does.

There are two considerations about this scenario:

a) A 2:1 power splitter should be inserted on the ONU side.

b) 50G ONU and DAW ONU should be both in ready state.

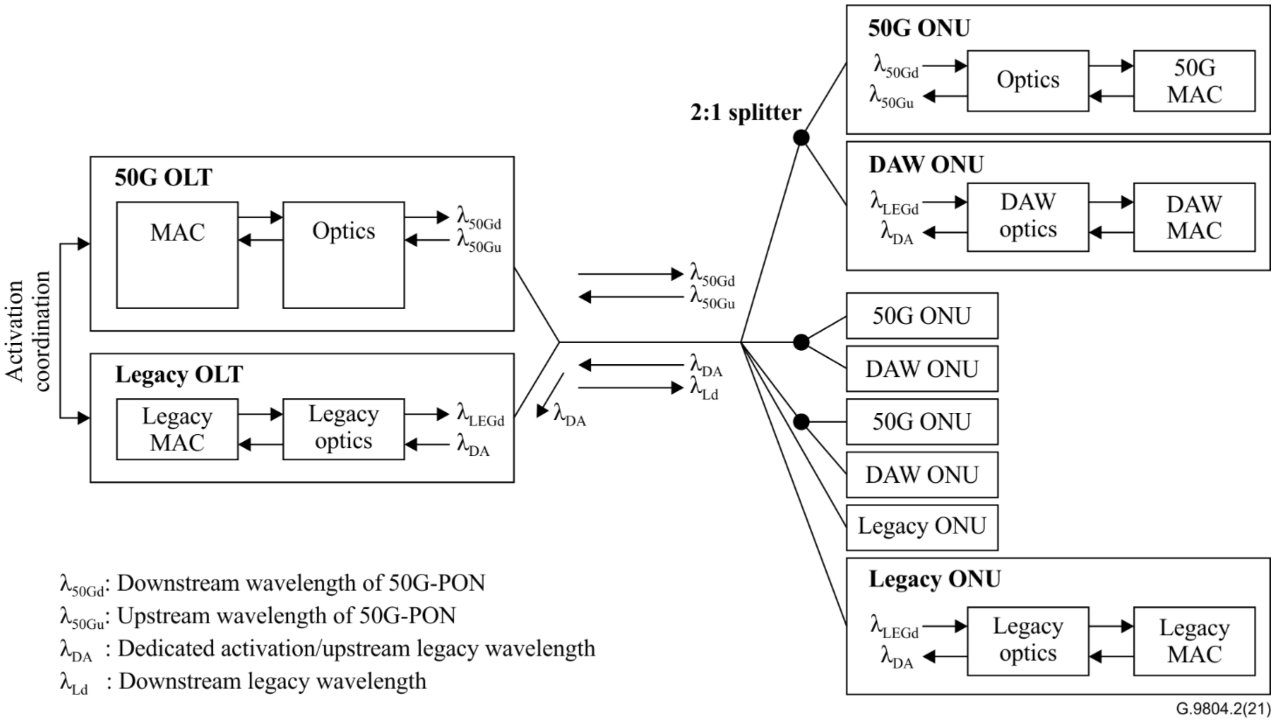


Figure IX.5 – Scenario C legacy dedicated activation wavelength

A comparison and summary of the DAW scenarios discussed above are shown in Table IX.1.

Table IX.1 – Comparison and summary of DAW scenarios

	Scenario A	Scenario B1	Scenario B2	Scenario B3	Scenario C
DAW	Newly defined wavelength	Legacy wavelength	Legacy wavelength	Legacy wavelength	Legacy wavelength
Impact on ODN	None	None	WDM1r + splitter	WDM	WDM + splitter
Legacy OLT	NA	Integrated with 50G OLT	Independent from 50G OLT	Independent from 50G OLT	Independent from 50G OLT
Change to legacy OLT	NA	Integrated with 50G OLT	Coordination with 50G OLT on quiet window	Coordination with 50G OLT on activation	Coordination with 50G OLT on activation
Working mechanism	Base activation	Base activation	Base activation + quiet window coordination	Base activation + activation information exchange	Base activation + activation information exchange + pair 50G ONU and DAW ONU

Appendix X

50G ONU synchronization state machine and transition criteria

(This appendix does not form an integral part of this Recommendation.)

This appendix describes example criteria of the transitions in the ONU reference synchronization state machine defined in Figure 10-4, which match synchronization performance metrics defined in Table 10-1 for 50G ONUs. It also provides suggested implementations of the reference synchronization state machine for 50G ONUs. The implementation of the ONU synchronization mechanism is vendor discretionary and may include a subset or a combination of mechanisms specified in this Appendix or other mechanisms that are not specified here. The performance of the suggested synchronization state machines meets the metrics defined in Table 10-1.

X.1 Transition criteria in ONU synchronization state machine

X.1.1 State machine transitions

The transitions defined in the ONU reference synchronization state machine and their possible implementations are listed in Table X.1. In case more than one condition/criterion for a transition is listed, implementers are free to use any of them or combined. Selection of a condition/criterion for each particular transition may, in certain conditions, improve or degrade synchronization performance, and is on the implementers.

Table X.1 – Transition criteria in ONU synchronization state machine

Transition	Related states	Condition/Criteria	Notes
Failure	Hunt → Hunt	Condition of PSync Found transition is not met	
PSync Found	Hunt → Pre-Sync	PSync with up to K_h errors is detected	Note 1
Tolerated Failures	Pre-Sync → Pre-Sync	Conditions Sufficient Success not met and PSync with no more than K_p errors is detected	Note 2
Excessive Failures	Pre-Sync → Hunt	PSync with more than K_p errors is detected	Note 2
Sufficient Success	Pre-Sync → Sync	1. Up to K_s errors in PSync 2. Up to K_s errors in PSync and no FEC decoding errors in a frame	Note 3
Success	Sync → Sync	None or very few FEC decoding errors per frame and up to K_s errors in PSync	Note 4
Failure	Sync → Re-Sync	1. PSync with more than K_s errors 2. Excessive FEC decoding errors	
Success	Re-Sync → Sync	Up to K_s errors in PSync and no FEC decoding errors in a frame	Note 4
Tolerated Failures	Re-Sync → Re-Sync	The Failure conditions persist	
Excessive Failure	Re-Sync → Hunt	The Sync → Re-Sync failure conditions persistence exceeds N frames	Note 5

NOTE 1 – The value of K_h for practical purposes can be derived from Figure X.1. Prior to transition into Pre-Sync, equalizer training is complete.

NOTE 2 – The value of K_p for practical purposes can be derived from Figure X.2. SFC errors may appear and should be tolerated. While in Pre-Sync state, the initial LLR computation is complete.

NOTE 3 – In normal operation even 1 FEC decoding error per frame is a rare event. The value of K_s for practical purposes can be derived from Figure X.3, which considers the PSync prior to LDPC decoding.

NOTE 4 – SFC errors may appear and should be tolerated.

NOTE 5 – The suggested value of N is defined in clause X.1.2.4.

X.1.2 Parameters of transitions

X.1.2.1 Parameters of PSync Found transition (Hunt → Pre-Sync)

The PSync Found transition is performed after PMD timing is locked. Convergence of the PMD clock recovery control loop and digital equalizer training is assumed to take place in Hunt state, prior to the PSync Found transition.

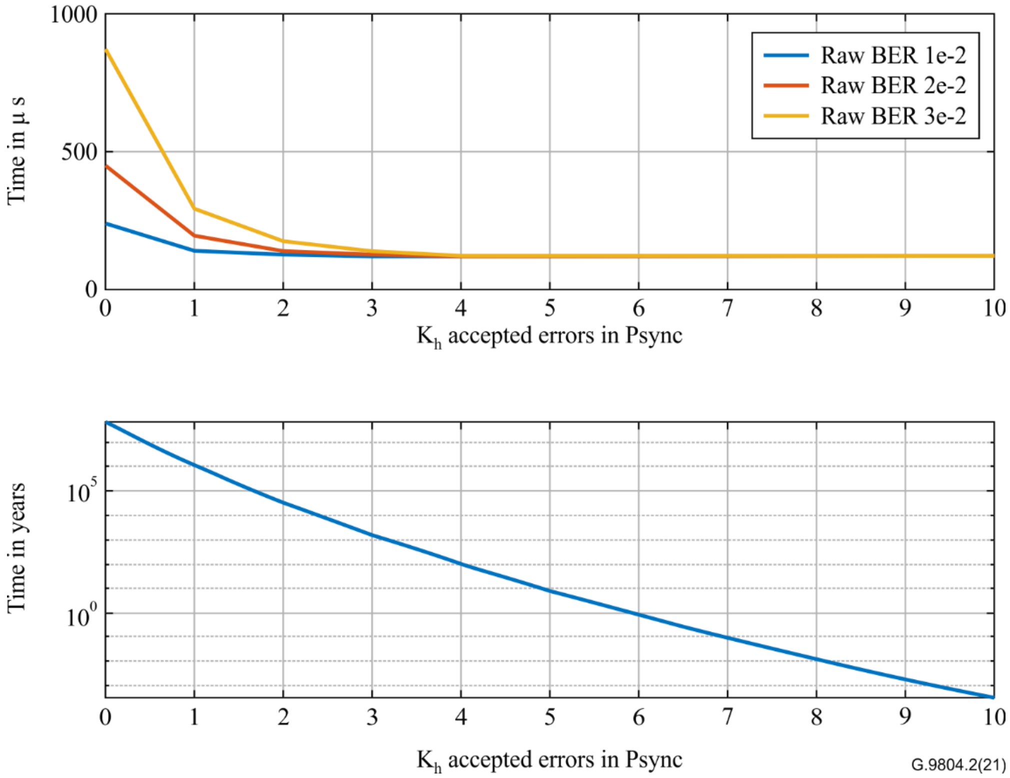


Figure X.1 – Mean times for a successful PSync Found transition (top) and for a false PSync Found transition (bottom) depending on the allowed number of errors, K_h

Figure X.2 can be uses as guidance to select the maximum number of errors K_h allowed the PSync pattern to perform PSync Found transition. A smaller value of K_h increases the mean time for PSync Found transition, but also increases the robustness against an un-intentional transition. Use of $K_h = 3$ gives a mean time between two false transitions of 1000 years while the probability for a fast successful transition during the very first frame checked is high.

X.1.2.2 Parameters of Excessive Failure transition (Pre-Sync → Hunt)

The ONU returns from Pre-Sync state back to Hunt state in case that $K_p > K_h$ errors are detected in the PSync pattern. To keep transition into Pre-sync state stable, $K_p = 10$ is suggested; it gives a sufficiently low probability to leave the pre-sync state unintentionally. Use of other values of K_p is shown in Figure X.2.

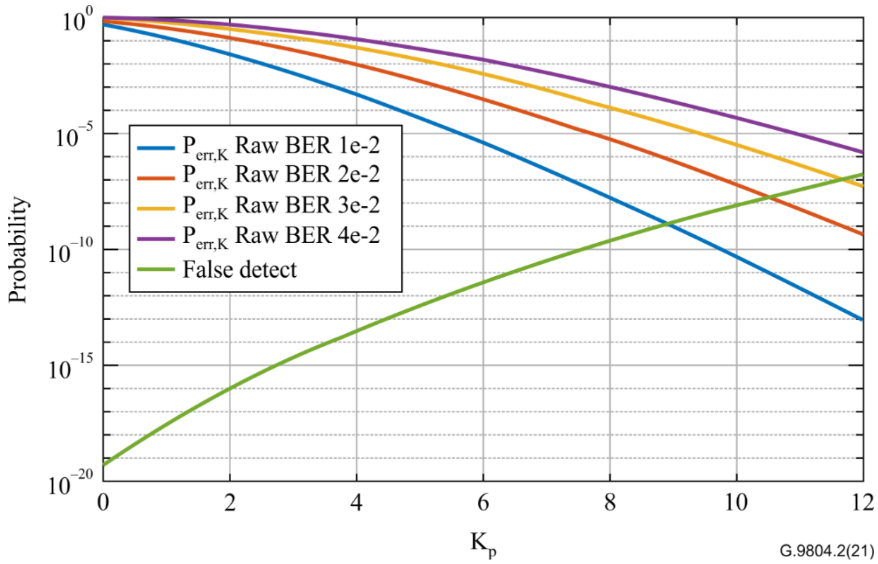


Figure X.2 – Probability of more than K_p errors in the PSync taken before the LDPC decoding when in sync vs less or equal to K_p errors when not in sync for different values of the raw BER (prior to LDPC decoding)

X.1.2.3 Parameters of Sufficient Success transition (Pre-Sync → Sync)

The transition from Pre-sync to Sync state is performed when the number of errors in the PSync pattern is less than K_h while the number of LDPC decoding errors in a frame is zero. The use of the FEC detection as an additional criterion is necessary to avoid a transition into sync state without working FEC.

NOTE – The LDPC decoding requires correct descrambling, which can only be performed after a valid SFC is received, i.e., with up to 2 errors that are correctable by the HEC-protection of the SFC structure (see Table A.4 of [ITU-T G.987.3] for the HEC verification rules).

When using FEC detection as a criterion, the synchronization time depends on the LDPC codeword error rate. At the target output bit error rate of 10^{-12}, the codeword error rate is below 10^{-9} and, accordingly, the probability of one or more LDPC decoding errors in a frame is less than 10^{-6}. Therefore, the probability that transition time from Pre-sync to Sync state occurs after one frame (125μs) is very high.

X.1.2.4 Parameters of Failure and Excessive Failure transitions (Sync → Re-Sync → Hunt)

For the transition from Sync to Re-Sync state (Failure transition), use of $K_s > K_h$ is recommended to exclude overreaction on occasional error events in PSBd. Selection of K_s is clarified in Figure X.3, when considering the example of the PSync taken before the FEC decoding and of a reference BER of 2.3×10-2, $K_s = 8$.

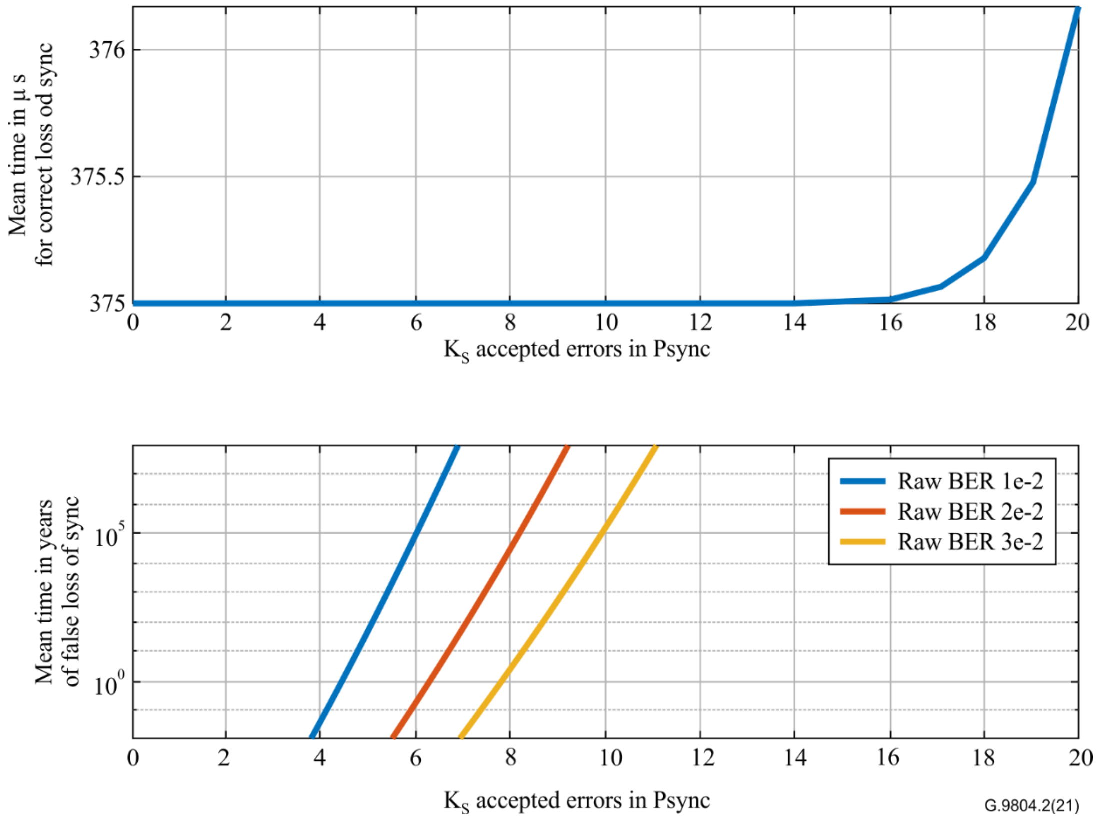


Figure X.3 – Mean time of a correct loss of sync and a false loss of sync, depending on K_s

The number N of consecutive frames with persistent failure conditions depends on the selected Sync to Re-Sync transition criteria. In case only PSync error condition is selected, N = 3 corresponds to very low probability of false sync loss (~ once in thousand years). If meeting both PSync error and LDPC decoding error conditions is selected as a criterion, using of N = 2 is usually sufficient.

X.1.3 Role of the interleaving mode

As defined in clause 10.5, interleaving mode (ON or OFF) is determined solely by the OLT CT and is generally unknown to the ONU. If interleaving is ON, since PSBd is a part of the first codeword, the bits of the PSBd, including PSync, are interleaved with data bits (see clause 10.5), which is not the case when interleaving is OFF. The ONU detects the mode of the interleaving while in the Hunt state, by searching PSync for both options, either sequentially or in parallel.

Incorrect detection of the interleaving mode, if occurs, will be discovered in the Pre-Sync state based on the criteria for Excessive Failures defined in Table X.1; the state machine will go back to Hunt, thus increasing the mean time to correct lock.

In some cases, e.g., a Type B protection switching, the ONU re-synchronizes with no change of the interleaving mode. To get shorter synchronization time, as defined in Table 10-1, the ONU should re-synchronize assuming the same interleaving mode as it was during its last Sync state. This approach is also beneficial after any sync loss since change of interleaving mode is expected to be a rather rare event.

X.2 ONU synchronization state machine

X.2.1 PSync and SFC decoded verification

Figure X.4 shows a synchronization state machine with both PSync and SFC decoded verification.

The ONU begins in the Hunt state. While in the Hunt state, the ONU searches for the PSync pattern in all possible alignments (both bit and byte, interleaved and non-interleaved) within the downstream signal. Once a match with the PSync pattern specified in clause 10.1.1.1 is found, the ONU can verify whether the 64 SFC bits form a valid (i.e., error-free or correctable) HEC-protected SFC structure (see Table A.4 of [ITU-T G.987.3] for the HEC verification rules). The PSync match is considered successful if at least ($64 - K_h$) bits of the 64-bit sequence match the fixed PSync pattern; otherwise, the PSync match fails. The value of K_h is the maximum number of allowed errors for one PSync pattern match (see clause X.1.2.1). The recommended value of the parameter K_h is 3. If the 64-bit protected SFC structure is uncorrectable, the ONU remains in the Hunt state and continues searching for a PSync pattern. If the 64-bit protected SFC structure is valid, the ONU stores a local copy of the SFC value and transitions into the Pre-Sync state.

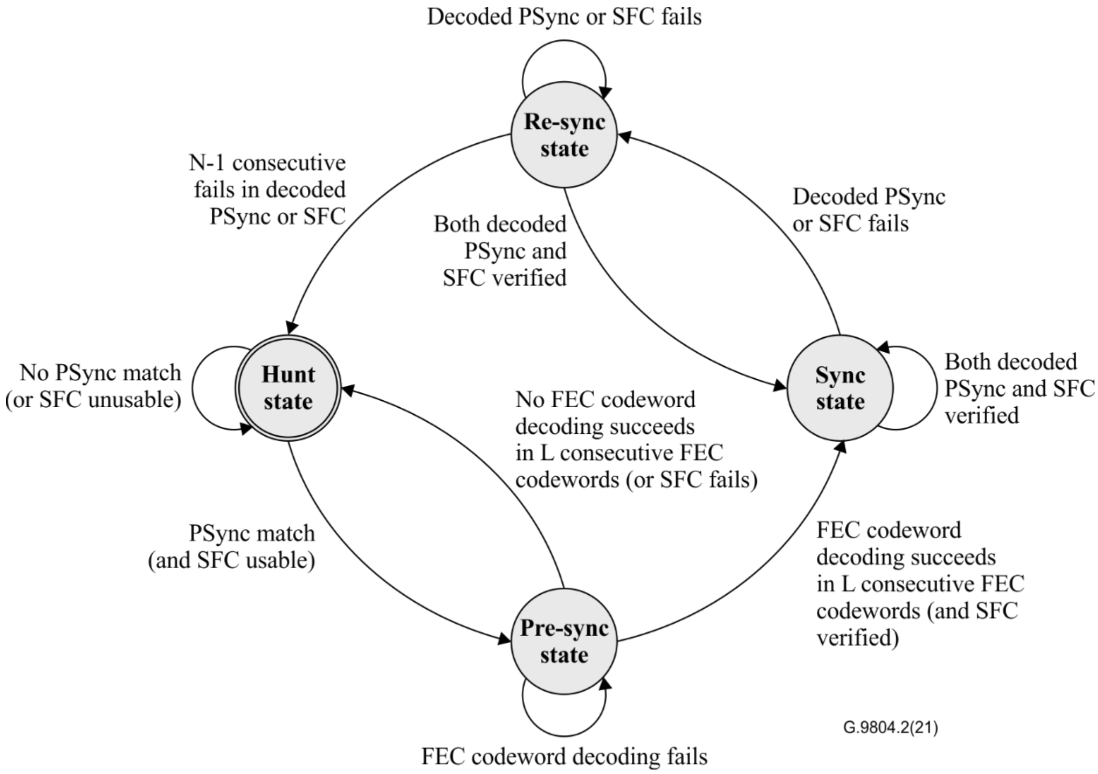


Figure X.4 – ONU synchronization state machine with PSync and SFC decoded verification

Once the ONU detects the PSync and usable SFC, it locates a boundary of a downstream PHY frame and transitions from the Hunt state to the Pre-Sync state. In the Pre-Sync state, the ONU can find the boundary of the FEC codeword and performs FEC codeword decoding in the PHY frame. Prior to SFC verification, the ONU increments the local SFC value by one.

Once in the Pre-Sync state, the ONU remains in the Pre-Sync state as long as the decoding of a FEC codewords fails. If the decoding of a FEC codeword is successful (and the SFC verification is successful in the following PHY frame) then the ONU transitions to the Sync state. If for L consecutive FEC codewords the decoding fails (or the SFC verification fails in the following PHY frame), the ONU returns to the Hunt state.

Once in the Sync state, the ONU continues to perform downstream FEC codeword decoding. As the PSync and SFC are protected by FEC, the ONU can use the PSync and SFC after FEC decoding (decoded PSync and SFC) while the errors are corrected to verify the synchronization state. The ONU remains in Sync state as long both decoded PSync verification and decoded SFC verification are successful, and transitions into the Re-Sync state, if either decoded PSync or SFC verification fails.

Once in the Re-Sync state, the ONU transitions back to Sync state if both decoded PSync and SFC are successfully verified once. However, for $N - 1$ consecutive PHY frames, if decoded PSync verification and/or decoded SFC verification fails, the ONU declares loss of downstream synchronization, discards the local SFC copy, and transitions into the Hunt state. The recommended value of the parameter L is 3. The recommended value of the parameter N is 3.

X.2.2 PSync only verification

Figure X.5 shows the synchronization state machine based on the detection of only the PSync.

The ONU begins in the Hunt state. While in the Hunt state, the ONU searches for the PSync pattern in all possible alignments (both bit and byte, interleaved and non-interleaved) within the downstream signal. The PSync verification is successful if at least $(64 – K_h)$ bits of the 64-bit sequence match the fixed PSync pattern; otherwise, the PSync verification fails. The value of K_h is the maximum number of allowed errors for one PSync pattern match (see clause X.1.2.1). The recommended value of the parameter K_h is 5. If the PSync pattern verification is successful, the ONU transitions forward into the Pre-Sync state. If the PSync pattern verification fails, the ONU remains in the Hunt state and continues searching for a PSync pattern.

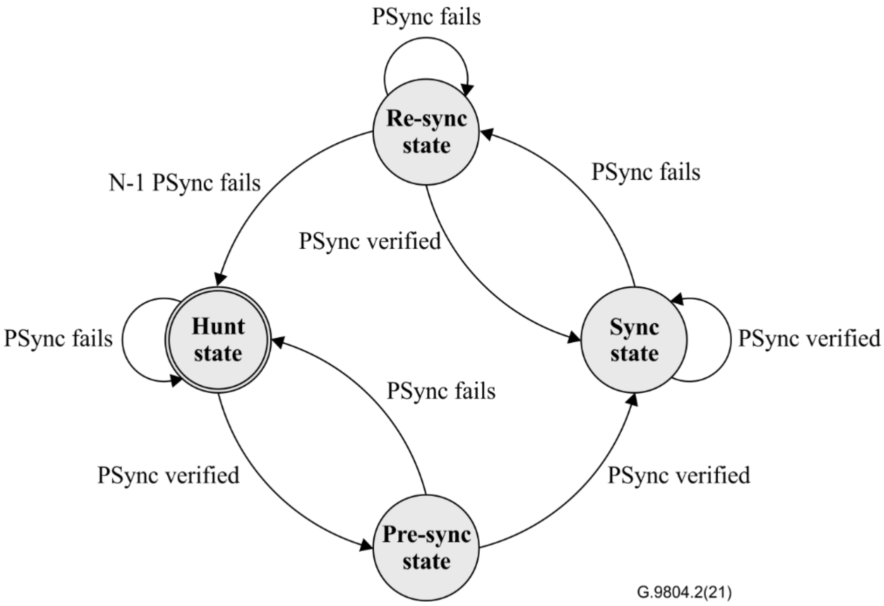


Figure X.5 – ONU synchronization state machine based on PSync detection

Once the ONU detects the PSync, it locates a boundary of a downstream PHY frame and transitions from the Hunt state into the Pre-Sync state. In the Pre-Sync state, the ONU performs PSync verification on each subsequent PHY frame and executes a corresponding transition of the downstream synchronization state machine.

Once in the Pre-Sync state, the ONU transitions into the Sync state if PSync verification is successful, or return to the Hunt state if PSync verification fails.

Once in the Sync state, the ONU continues to perform PSync verification. The ONU remains in Sync state as long the PSync verification is successful, or transitions into the Re-Sync state if the PSync verification fails.

Once in the Re-Sync state, the ONU transitions back to the Sync state if PSync can be successfully verified once. However, if for $N – 1$ consecutive PHY frames the PSync verification fails, then the ONU declares loss of downstream synchronization and transitions into the Hunt state. The recommended value of the maximum number of consecutive PSync mismatches (N) is 3.

X.2.3 FEC decoding

Figure X.6 shows a synchronization state machine with FEC decoding.

The ONU begins in the Hunt state. While in the Hunt state, the ONU searches for the PSync pattern in all possible alignments (both bit and byte, interleaved or non-interleaved) within the downstream signal. Once a match with the PSync pattern is found, the ONU verifies whether the 64 SFC bits of the PSBd form a valid (i.e., error-free or correctable) HEC-protected SFC structure (see Table A.4 of [ITU-T G.987.3] for the HEC verification rules). The PSync match is successful if at least ($64 – K_h$) bits of the 64-bit sequence match the PSync pattern; otherwise, the PSync match fails. The value of K_h is the maximum number of allowed errors for one PSync pattern match (see clause X.1.2.1). The recommended value of the parameter K_h is 3. If the 64-bit protected SFC structure is uncorrectable, the ONU remains in the Hunt state and continues searching for a PSync pattern. If the 64-bit protected SFC structure is valid, the ONU stores a local copy of the SFC value and transitions into the Pre-Sync state.

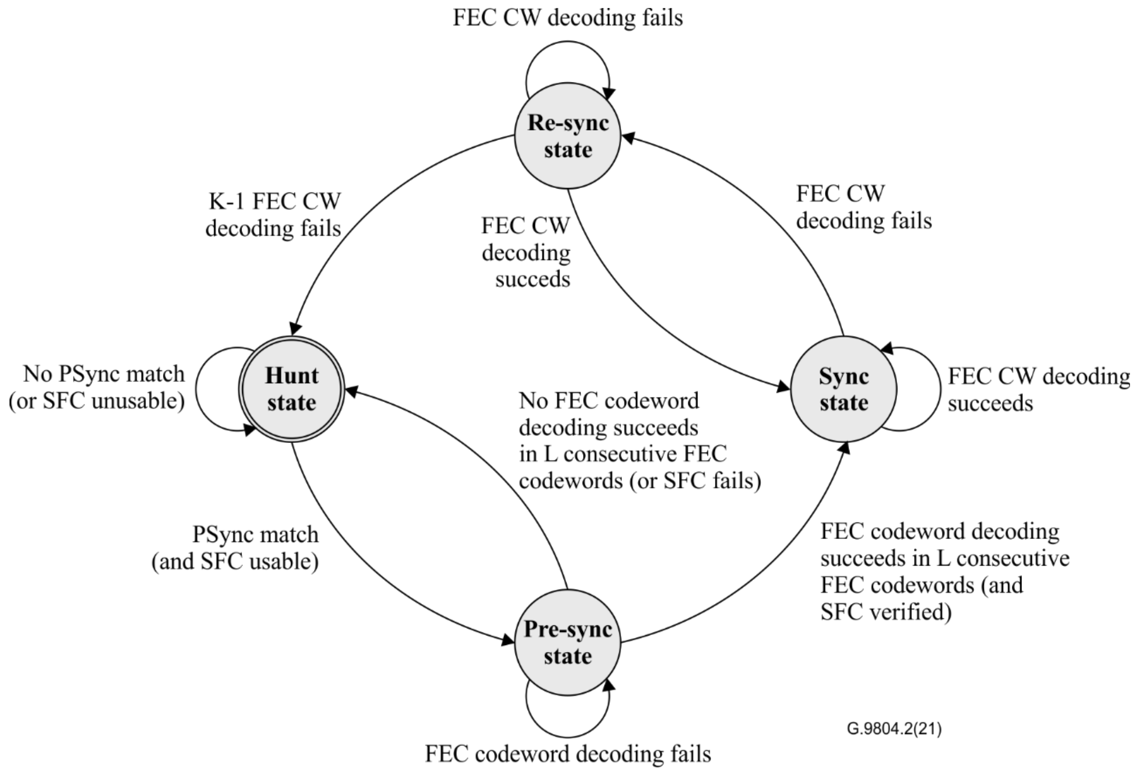


Figure X.6 – ONU synchronization state machine with FEC decoding

Once the ONU detects the PSync, it locates a boundary of a downstream PHY frame and transitions from the Hunt state into the Pre-Sync state. In the Pre-Sync state, the ONU finds the boundary of the FEC codeword and performs FEC codeword decoding in the PHY frame. Prior to SFC verification, the ONU increments the local SFC value by one.

Once in the Pre-Sync state, the ONU remains in the Pre-Sync state as long as the decoding of a FEC codewords fails. If the decoding of a FEC codeword is successful (and the SFC verification is successful in the following PHY frame) then the ONU transitions to the Sync state. If for L consecutive FEC codewords the decoding fails (or the SFC verification fails in the following PHY frame), the ONU returns to the Hunt state.

Once in the Sync state, the ONU remains in that state as long as decoding of a FEC codeword is successful, and transitions into the Re-Sync state, if decoding of a FEC codeword fails.

Once in the Re-Sync state, the ONU transitions back to Sync state if decoding of a FEC codeword is successful once. However, if for $K – 1$ consecutive FEC codewords decoding fails, the ONU declares loss of downstream synchronization, discards the local SFC copy, and transitions into the Hunt state. The recommended value of the parameters *L and K* is 5.

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