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Review

Lasers in Passive Optical Networks and the Activation Process of an End Unit: A Tutorial

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Received: 19 June 2020; Accepted: 6 July 2020; Published: 9 July 2020

Abstract: It is 21 years since the first passive optical network (PON) was standardized as an asynchronous transfer mode passive optical network (APON) with same optical distribution network scheme as we know in current networks. A lot of PON networks were standardized in the following years and became an important part of telecommunication. The general principles of these PON networks are described in many papers and books, but only a little information about used lasers is available. The aim of this tutorial is to describe lasers used in PON networks and principles of their operation. The paper describes the principles of single longitudinal mode (SLM), multi longitudinal mode (MLM), distributed-feedback (DFB), and Fabry–Pérot (FP) lasers. Furthermore, the lasers are compared by their usage in optical line termination (OLT) for passive optical networks. The second part of this tutorial deals with activation process of optical network unit. The described principle is the same for connection of a new customer or blackout scenario. The end unit is not able to communicate until reach the operational state; each state is defined with physical layer operation and administration and maintenance (PLOAM) messages sequence and their processing.

Keywords: single longitudinal mode laser; multi longitudinal mode laser; distributed-feedback laser; Fabry-Pérot laser; activation process; PLOAM messages

1. Introduction

A passive optical network (PON) is a cabling system that uses optical fibers and optical splitters to deliver services to multiple access points. A passive optical network has only passive components and is capable of handling the data-centric demands arising from both the home and enterprise networks. In bringing fiber to the home, the PON has played a major role.

The bitrate of the first passive optical network was 155 Mbps in the downstream direction. During this time, PONs were innovated in many ways, and the bitrate increased to 100 Gbps [1–9]. The evolution of PONs is shown in Figure 1.

PONs consist of three main parts [10]:

- Optical line terminal (OLT)—interface between Internet service provider (ISP) and access network.
- Optical network unit (ONU)—interface between optical and metallic networks.
- Optical distribution network (ODN)—optical link between OLT and ONU.

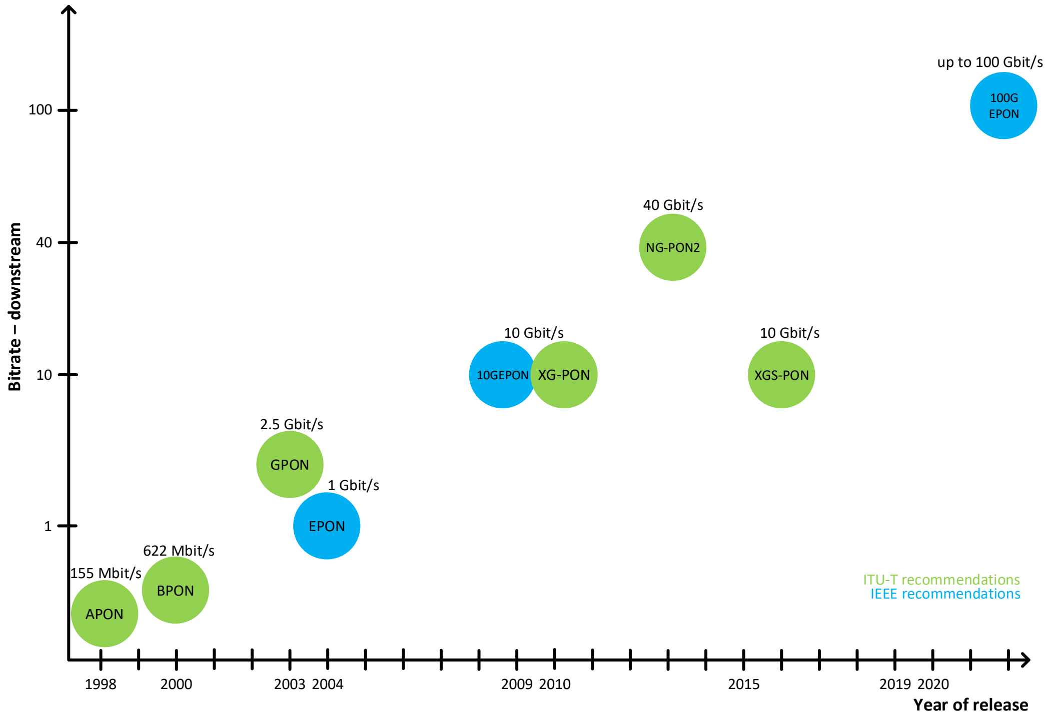

Figure 1. Passive optical network (PON) evolution [1,11–16].

A typical PON shows the origin of the service network at an OLT that is normally in a head office or central unit of the network [17]. The services are then carried along an optical feeder extending up to 20 km (or longer) of fiber distance, eventually splitting the optical power into multiple distribution fibers using a splitter that resides on a remote node. Each distribution fiber carries the service to the destined optical network unit, which is the termination point of the optical signal; this signal is then distributed to all end users connected to this ONU.

The rest of this paper is organized as follows. Section 2 provides a brief introduction of the passive optical network standards, with the principles of communication and the laser sources used for their communications. Section 4 describes the activation process of the optical network unit in a gigabit passive optical network after a blackout or after a new customer is added to the ISP network. Section 5 concludes this tutorial.

2. PON Standards

2.1. APON and BPON

The asynchronous transfer mode PON (APON) was the first standardized PON according to the International Telecommunication Union Telecommunication sector (ITU-T) G.983 in 1998. Data were transferred by (ATM) cells with a bit rate of 155 Mbps symmetrically or asymmetrically with a downstream rate of 622.08 Mbps [18,19]. In 2000, the APON was extended to the broadband PON (BPON). The difference between the APON and BPON is the use of a wavelength multiplex for the separation of downstream and upstream. The bitrate was extended to 622.08 Mbps symmetrically [11,20].

2.2. GPON

The next PON in a row was a gigabit PON (GPON), standardized as ITU-T G.984 in 2003. The GPON is back-compatible with the APON/BPON, and the bitrate was extended to 1.244 Gbps or 2.488 Gbps, respectively. The maximal reach is 20 km, with a maximal split ratio of 1:64. The GPON is still the most frequently used PON around the world [14].

2.3. XG-PON

The next-generation PON (XG-PON) was standardized in 2010 as ITU-T G.987, and the bitrate was extended to 9.953 Gbps downstream and 2.455 Gbps upstream [21,22]. Only an asymmetrical bitrate is available for this standard. The maximal split ratio was extended to 1:256 with a reach up to 20 km. The XG-PON is back-compatible with the GPON because different wavelengths are used [15].

2.4. EPON

The Ethernet PON (EPON) is the first type of passive optical network standardized by the Institute of Electrical and Electronics Engineers (IEEE) in 2004 as IEEE 802.3ah. Data are transformed by Ethernet frames according to the Ethernet standard. The maximal reach is 20 km with a split ratio of 1:32. The bitrate is 1.25 Gbps symmetrically [12]. The standard defines two types: EPON1 (1000BASE-PX10) and EPON2 (1000BASE-PX20). EPON1 allows a maximal reach of 10 km and a split ratio of 1:16, and EPON2 allows 20 km and a split ratio of 1:32.

2.5. 10GEPON

The latest standard IEEE 802.3av was released in 2009. The 10GEPON is back-compatible with the EPON. The maximal bit rate is 10.3125 Gbps symmetrically. The maximal reach is 20 km with a split ratio of 1:32 [13].

2.6. NG-PON2

The next-generation PON stage 2 (NG-PON2) was standardized in 2015 as ITU-T G.989. This standard combines time division multiplexing (TDM) with wavelength division multiplexing (WDM). The NG-PON2 supports 4–8 wavelengths with a bitrate of 10 Gbps per lambda. The total network throughput is 80 Gbps over one single fiber [23,24]. The maximal reach is 40 km with a split ratio of 1:256. The NG-PON2 is back-compatible with the GPON and XG-PON via coexistence element (CE); see Figure 2 [16].

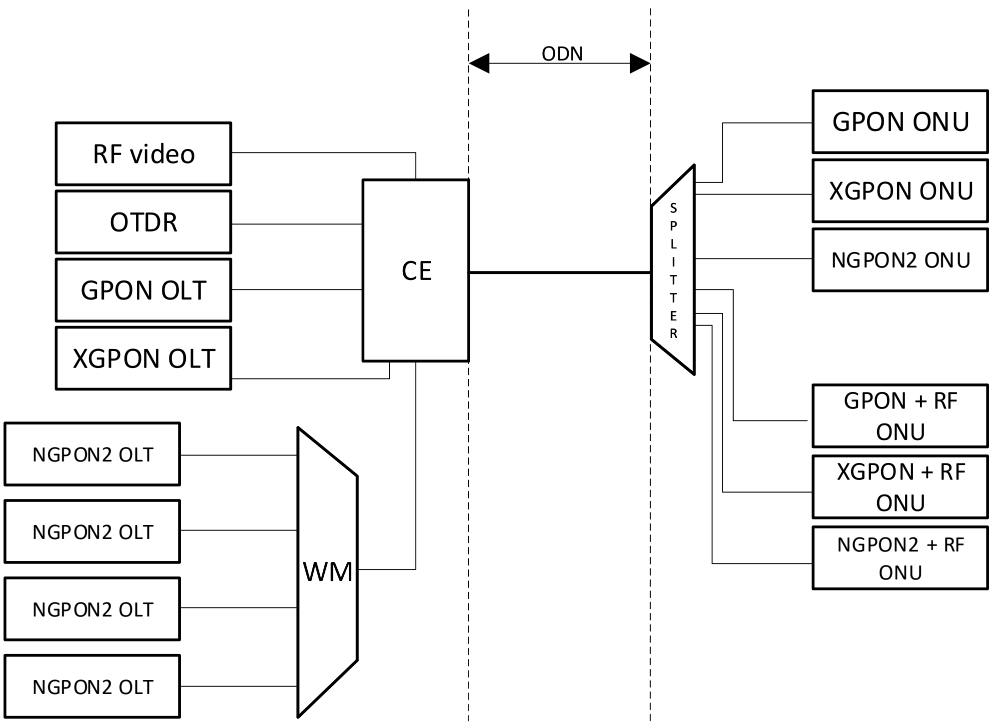

Figure 2. Principle of NG-PON2 coexistence [16].

2.7. WDM-PON

A special category, which has not yet been standardized, is a wavelength division multiplex PON (WDM-PON). The WDM-PON was introduced by LG-Nortel (LG-Ericson) in 2010 but was not massively used because of its high price. There are many ways to realize the WDM-PON, but the most general principle is based on a set of distributed feedback (DFB) lasers in the OLT, the arrayed waveguide grating (AWG) and the ONU with DFB or Fabry–Pérot (FP) lasers. LG-Nortel used 32 wavelengths in the C-band with a 100 GHz (0.8 nm) channel spacing [25–27].

3. Principle of PONs

Except for WDM-PONs, all PONs are based on TDM. This multiplexing technique is widely used because of its easy implementation. On the other hand, WDM is used in core and metropolitan networks for a long time. The NG-PON2 combines both multiplexes and allows effective usage of the bandwidth.

3.1. TDM

Thanks to the high redundancy of the transmission capacity and the time diversity of their usage, it is possible to divide transmission capacity into time slots, which are assigned to end users (downstream) [1,28]. Recognition of the beginning and end of each time slot is achieved by using additional headers for each frame. If the time slots have the same length, it is possible to synchronize the multiplexer and demultiplexer by a special synchronization interval. We can say that it is the coding of each of the channels to electric pulses, which are converted to optical signals. Downstream, the DFB laser in the OLT is directly modulated by the control system. Upstream, each data stream from the end users is stacked into defined time intervals, which form the final data stream towards the OLT unit. The principle of TDM in PONs is shown in Figure 3. To avoid mutual collisions, the OLT unit transmits information cells downstream (based on the knowledge of the delay caused by signal spreading from each of the ONUs) with transmitting time allocated for each ONU. At this allocated time, the ONU guarantees that no other ONU will transmit at the same time. In addition, a so-called protecting time interval is inserted between the cells as a part of the extended frame header [14]. It is obvious that it is not possible to use a continual wave (CW) laser upstream. The upstream mode is also called "burst" due to the allocated time slots in which the ONU transmits the signal. It is possible to use a DFB or FP laser, depending on the PON standard. The parameters of all the PON standards are compared in Table 1 for ITU-T and in Table 2 for the IEEE standards.

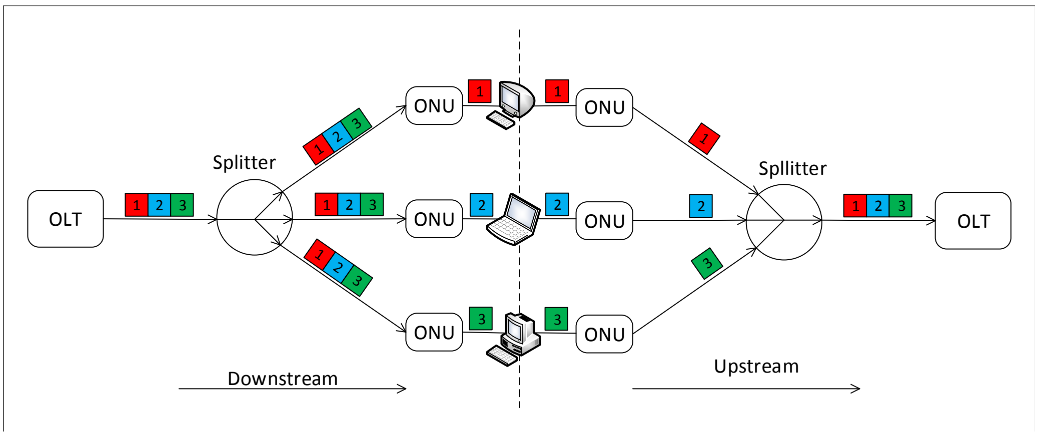

Figure 3. Principle of TDM in a PON.

Table 1. Parameters of the ITU-T PONs.

Standard	APON/BPON	GPON	XG-PON	NG-PON2
ITU-T	ITU-T G.983	ITU-T G.984	ITU-T G.987	ITU-T G.989
Year of release	1998	2003	2010	2015
P_d [Gbit/s]	0.155/0.622	1.224/2.488	9.953/2.455	40/10
P_u [Gbit/s]	0.155/0.622	1.224/2.488	2.455	40/10
λ_d [nm]	1 480–1 500	1 480–1 500	1 575–1 580	1 596–1 603
λ_u [nm]	1 260–1 360	1 260–1 360	1 260–1 280	1 524–1 544
Split ratio	1:16	1:64	1:256	1:256
Reach [km]	20	20	20	60
Laser type Down.	MLM/SLM	SLM	SLM	SLM
Laser type Upstr.	MLM/SLM	MLM/SLM	SLM	SLM

Table 2. Parameters of the Institute of Electrical and Electronics Engineers (IEEE) PONs.

Standard	EPON	10GEPON
IEEE	IEEE 802.3ah	IEEE 802.3av
Year of release	2004	2009
P_d [Gbit/s]	1.25	10.3125
P_u [Gbit/s]	1.25	10.3125/1.25
λ_d [nm]	1 480–1 500	1 570–1 600
λ_u [nm]	1 260–1 360	1 260–1 360
Split ratio	1:16/1:32	1:32
Reach [km]	10/20	20
Laser type Down.	MLM/SLM	SLM
Laser type Upstr.	MLM/SLM	SLM

3.2. WDM

The idea of wavelength multiplexing is to combine more optical signals with different wavelengths (frequencies) to one optical fiber. Transmitted information is modulated to a specific frequency. N-channel signals are combined in a multiplexer and transmitted into one optical fiber. The principle of WDM in PONs is shown in Figure 4. There are three main WDM types—wide WDM (WWDM), coarse WDM (CWDM) and dense WDM (DWDM). Currently, only DWDM can be used for the WDM-PON or NG-PON2. The spectral spacing between DWDM channels is 0.8 or 0.4 nm [29].

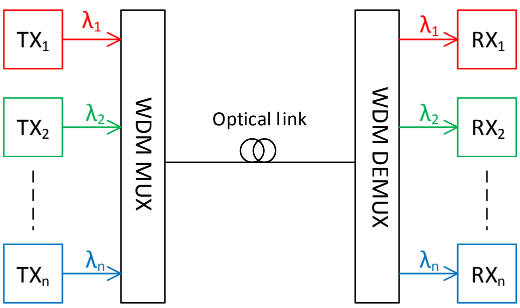

Figure 4. Principle of WDM in a PON.

3.3. SLM and MLM Lasers

Semiconductor lasers are popular optical communication light sources for high-speed data transmission. They are compact, are easy to integrate and have high output power. Coherent emission is produced in these lasers by stimulated emission, and the gain is achieved in the active medium of the semiconductor by electrical injection. Semiconductor lasers are very efficient in converting electrical power into optical power [30]. In PONs, two types of semiconductor lasers are used: single longitudinal mode (SLM) lasers and multilongitudinal mode (MLM) lasers. There are more types of SLM and MLM lasers, but for PONs, DFB (SLM type) and FP (MLM type) lasers are the only ones that are used.

The FP laser is mainly used for low-data-rate and short-distance transmission; the transmission distance is generally within 20 km, and the bitrate is generally within 1.25 Gbps. FP lasers are manufactured mainly for two wavelengths: 1310 nm and 1550 nm.

DFB lasers use a grating filter to make the device have only one longitudinal mode output based on the FP laser. DFB generally also involves two wavelengths, i.e., 1310 nm and 1550 nm, divided into cooled and non-cooled, which are mainly used for high-data-rate and long-distance transmission. The transmission distance is generally more than 40 km, with a bitrate higher than 10 Gbps.

The main difference between the FP and DFB lasers is that the spectral widths are different. The spectral width of the DFB laser is narrow, being a single longitudinal mode laser with distributed negative feedback. The spectral width of the FP laser is relatively wide, being a multilongitudinal mode laser. The working wavelength, threshold current and voltage are also different.

3.4. DFB Lasers

A distributed-feedback laser is one in which the whole resonator consists of a periodic structure, which acts as a distributed reflector in the wavelength range of laser action, and contains a gain medium. Typically, the periodic structure is made with a phase shift in its middle. This structure is essentially the direct concatenation of two Bragg gratings with optical gain within the gratings (see Figure 5). The device has multiple axial resonator modes, but there is typically one mode which is favored in terms of losses. Therefore, single-frequency operation is often easily achieved, despite spatial hole burning due to the standing-wave pattern in the gain medium. Due to the large free spectral range, wavelength tuning without mode hops may be possible over a range of several nanometers. However, the tuning range may not be as large as for a distributed Bragg reflector laser [31].

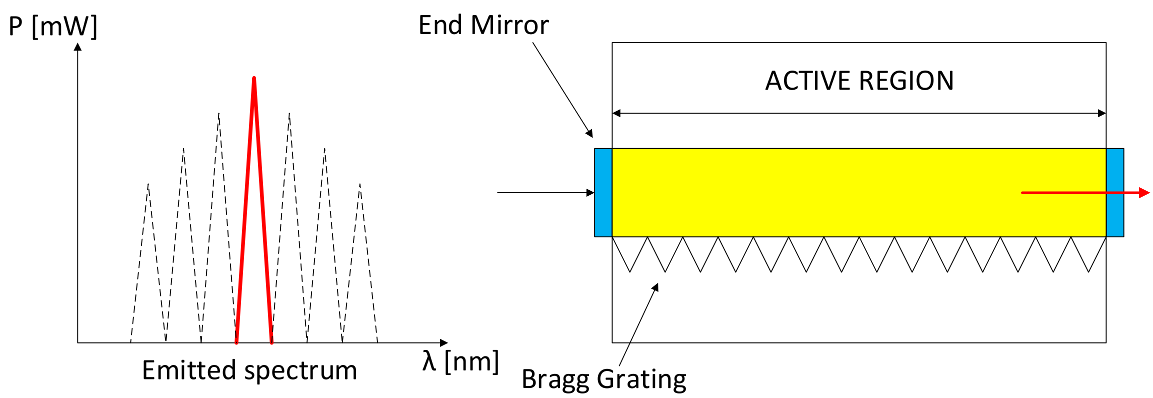

Figure 5. Schematic diagram of the DFB laser.

Most distributed-feedback lasers are either fiber lasers or semiconductor lasers, operating in a single resonator mode. In the case of a fiber laser, the distributed reflection occurs in a fiber Bragg grating, typically with a length of a few millimeters or centimeters. Efficient pump absorption can be achieved only with a high doping concentration of the fiber, and unfortunately, it is often not easy to write Bragg gratings into fibers with a composition (e.g., phosphate glass) that allows for a high doping concentration. Therefore, the output power is usually fairly limited (e.g., to a few tens of milliwatts). However, this kind of single-frequency fiber laser is very simple and compact. Its compactness and robustness also lead to a low intensity and phase noise level, i.e., also a low line width, although the fundamental line width limit (the Schawlow–Townes line width) is higher than for longer fiber lasers [31].

Semiconductor DFB lasers can be built with an integrated grating structure, e.g., a corrugated waveguide. The grating structure may be produced on top of the active region, which unfortunately requires time-consuming regrowth techniques. An alternative is to make laterally coupled structures, where the gratings are on both sides of the active region. Semiconductor DFB lasers are available for emission in different spectral regions, at least in the range from 800 to 2800 nm. Typical output powers are some tens of milliwatts. The line width is typically a few hundred MHz, and wavelength tuning is often possible over several nanometers. Temperature-stabilized devices, as used, e.g., in DWDM systems, can exhibit a high wavelength stability [32].

The temperature coefficient of the wavelength is under 0.1 nm/K. Because only a single longitudinal mode is present, a DFB does not suffer from mode partition noise. DFB lasers are generally more expensive than FP lasers. The lasing wavelength varies at 0.1 nm/K, while its gain peak varies at around 0.45 nm/K [12].

3.5. FP Lasers

In Fabry–Pérot lasers, optical feedback is achieved by the cleaved facets of the diode, which causes the laser action to occur (see Figure 6). This results in FP lasers as edge-emitting diode lasers. The emission is produced at the longitudinal modes of the cavity and can be tuned by tuning the cavity length [33]. A laser oscillator has two mirrors separated by an amplifying medium with an inverted population, making a Fabry–Pérot cavity.

FP lasers are a very well-developed technology and are readily available for many commercial applications. FP lasers could use a single mode or multimode output and allow internal modulation, which is important for miniaturization and use in PONs [34].

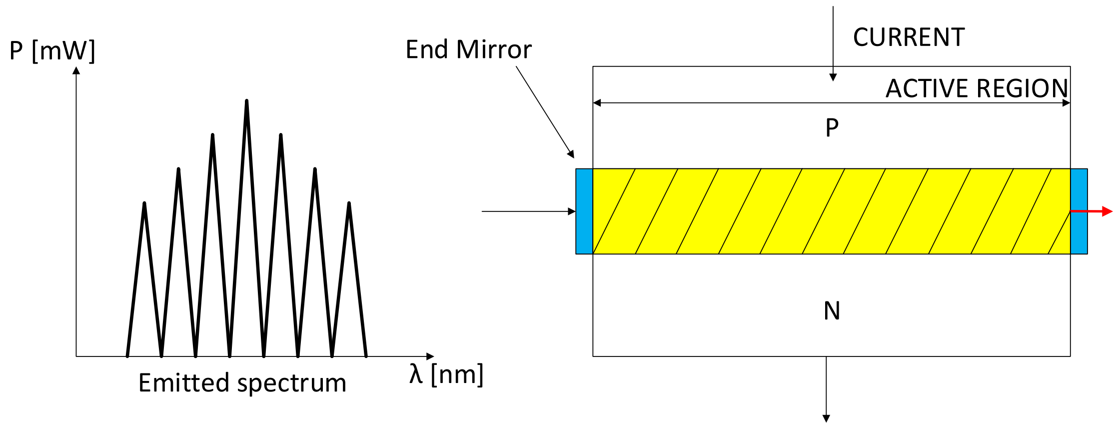

Figure 6. Schematic diagram of the FP laser.

A Fabry–Pérot cavity is a standard cavity with two highly reflecting mirrors that bounce light back and forth, forming a standing wave. This cavity is not very frequency selective; theoretically, you could have 1 mm wavelength light and 1 nm wavelength light in the same cavity, as long as the mirrors are the right distance apart to form a standing wave. Fabry–Pérot lasers are made with a gain region and a pair of mirrors on the facets, but the only wavelength selectivity is from the wavelength dependence of the gain and the requirement of an integral number of wavelengths in a cavity round trip. A Fabry–Pérot cavity by definition consists of two planar mirrors, but the term is currently very frequently also used for resonators with curved mirrors. From a theoretical viewpoint, plane–plane optical resonators are special in the sense that their resonator modes extend up to the edges of the mirrors and experience some diffraction losses. However, Fabry–Pérot lasers are usually used with input beams of much smaller diameter, which are actually not really matched to the resonator modes. For the usually small mirror spacings, where diffraction within a round trip is rather weak, this deviation does not matter that much [35].

Fabry–Pérot lasers may have a temperature coefficient of the wavelength around 0.45 nm/K; hence, the operating wavelength of a particular FP may vary by 55 nm over the range –40 to 85 °C. The operating wavelength windows for the EPON/GPON standard are generally 100 nm wide when FPs are anticipated, allowing an adequate margin for manufacturing tolerances. To allow for the widest variety of implementations, the spectral width is specified as a function of the wavelength where appropriate. However, the requirement for low error rates over substantial distances of a fiber, as specified by the transmitter and dispersion penalty, forces the user of 1000 Mb/s FP-laser-based implementations to pay careful attention to both the wavelength and spectral width to avoid excessive mode partition noise [12].

3.6. Requirements for PON Standards

Depending on the attenuation and dispersion characteristics of the optical distribution network, Fabry–Pérot (MLM) or distributed feedback (SLM) lasers could be used. For each of the applications, the ITU-T or IEEE recommendation indicates a nominal source type.

If the FP laser is used, the spectral width is specified by the maximum root mean square (RMS) width under standard operating conditions. The RMS width is understood to mean the standard deviation of the spectral distribution. The measurement method for RMS widths should take into account all modes that are not more than 20 dB down from the peak mode [11].

If the DFB laser is used, the maximum spectral width is specified by the maximum full width of the central wavelength peak, measured 20 dB down from the maximum amplitude of the central wavelength under standard operating conditions. Additionally, for control of the mode partition noise in SLM systems, a minimum value for the laser side-mode suppression ratio is specified. The laser requirements for ITU-T PONs are shown in Table 3.

MLM laser types are not able to support the full ODN fiber distance of 20 km; these lasers can be used if the maximum ODN fiber distance between OLTs and ONUs is restricted to 10 km. As we can see in Table 3, MLM lasers can be used only for APONs/BPONs with a bitrate of 155 Mbps or 622 Mbps in OLT units and for APONs/BPONs and GPONs with a bitrate of 155 Mbps or 622 Mbps in ONUs. The use of multilongitudinal mode (MLM) lasers is not considered in subsequent standards due to their practical distance/line rate limitations [11].

Considering the attenuation/dispersion characteristics of the target fiber channel, feasible transmitter devices include only single longitudinal mode (SLM) lasers for the XG-PON and NG-PON2 for all distance and line rate requirements of the XG-PON systems for both downstream and upstream links.

SLM lasers are specified by the fiber dispersion range, over which the laser characteristics and fiber dispersion result in a defined penalty at a specified fiber distance, under standard operating conditions. The actual spectral characteristics are limited by the maximum amount of optical path penalty produced with the worst-case optical dispersion in the data channel [15].

The IEEE standardization union has different systems for laser requirements. The MLM laser can be used in EPONs and 10GEPONs in the upstream direction (at ONUs). The requirements for MLM lasers are shown in Table 4. It is obvious that there is a difference between 1000BASE-PX10, 1000BASE-PX20 and 10/1GBASE-PRX—the claims for the FP lasers increase. We can say that for the 10GEPON, it is better to use DFB lasers upstream, and it is necessary to use DFB lasers downstream. For SLM lasers, the 20 dB width is taken as 6.07 times the RMS width. For the OLT units, only the DFB laser can be used, while for the 10GEPON, the side-mode suppression ratio must be 30 dB at a minimum.

Table 3. ITU-T laser requirements for PONs [11,14–16].

Standard	Nominal Bitrate Downstream (Mbps)	Items	OLT Transmitter	Unit
APON/BPON	155	MLM laser — maximum RMS width	1.8	nm
		SLM laser — maximum –20 dB	1.00	nm
		SLM laser — minimum side-mode suppression ratio	30.00	dB
	622	MLM laser — maximum RMS width	NA	nm
		SLM laser — maximum –20 dB	1.00	nm
		SLM laser — minimum side-mode suppression ratio	30.00	dB
	1244	MLM laser — maximum RMS width	NA	nm
		SLM laser — maximum –20 dB	1.00	nm
		SLM laser — minimum side-mode suppression ratio	30.00	dB
GPON	1244	MLM laser – maximum RMS width	NA	nm
		SLM laser — maximum –20 dB	1.00	nm
		SLM laser — minimum side-mode suppression ratio	30.00	dB
	2488	MLM laser — maximum RMS width	NA	nm
		SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
XGPON	9953	SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
NG-PON2	9953	SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
Standard	**Nominal Bitrate Upstream (Mbps)**	**Items**	**ONU Transmitter**	**Unit**
APON/BPON	155	MLM laser — maximum RMS width	5.8	nm
		SLM laser — maximum –2 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
	622	MLM laser — maximum RMS width	1.4/2.1/2.7	nm
		SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
GPON	155	MLM laser — maximum RMS width	5.8	nm
		SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
	622	MLM laser — maximum RMS width	1.4/2.1/2.7	nm
		SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
	1244	MLM laser — maximum RMS width	NA	nm
		SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
	2488	MLM laser — maximum RMS width	NA	nm
		SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
XGPON	2488	SLM laser — maximum –20 dB	1	nm
		SLM laser — minimum side-mode suppression ratio	30	dB
NG-PON2	2488	Not defined		
	9953			

Table 4. IEEE laser requirements for PONs [12,13].

CWL (nm)	RMS Spectral Width (nm)		
	1000BASE-PX10	1000BASE-PX20	10/1GBASE-PRX
1260	2.09	0.72	0.59
1270	2.52	0.86	0.7
1280	3.13	1.07	0.87
1286		-	-
1290		1.4	1.14
1297		-	-
1300		2.00	1.64
1304		2.5	1.98
1305		2.55	2.09
1308		3.00	2.40
1317	3.5	-	2.40
1320		2.53	2.07
1321		2.41	1.98
1320		-	2.07
1321		-	1.98
1329		-	-
1330		1.71	1.40
1340		1.29	1.06
1343		-	-
1350	3.06	1.05	0.86
1360	2.58	0.88	0.72
1480–1500	0.88	0.44	NA

4. ONU Activation Process in ITU-Based Passive Optical Networks

This section provides a detailed overview of the ONU activation process. The activation process is an important attribute of OLT because OLT is represented as a master and ONU is represented as a slave [36,37]. Due to point-to-multipoint (P2MP) topology, the OLT is able to activate a single ONU in each cycle of the activation process. If we consider a new network, then a large number of ONUs have to be activated during the first run [38]. The second scenario/situation occurs after the blackout. Although we take into account only one ONU, the steps are the same as those in other ONUs (each ONU has to start from the O1 state). The activation process starts by connecting a new ONU into an ODN (in general, a new customer's ONU).

4.1. State O1—Initial State

First, the loss of a frame/signal (LOF/LOS) parameter is asserted. Second, the ONU searchdx for the synchronization part in the GPON transmission convergence (GTC) frames of the OLT. A synchronization pattern (0xB6AB31E0) is always presented in each downstream frame (every 125 µs) because it identifies the beginning of the frame (the synchronization pattern is not scrambled). The total number of receiving synchronization patterns depends on each ISP preference (represented by N parameter). The first state is presented in Figure 7. Once the parameter N is attained, the ONU moves to the state O2.

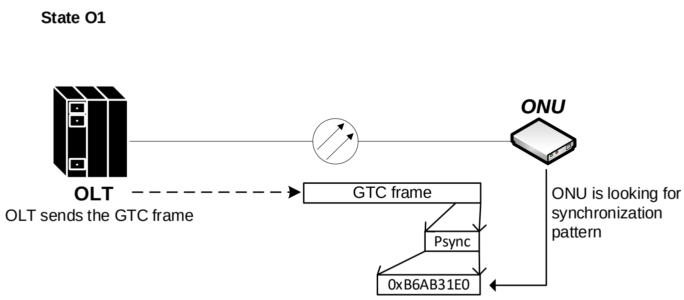

Figure 7. Activation process of ONU in a GPON network with PLOAM message details for state O1.

4.2. State O2—Standby State

The initial state ensures synchronization with downstream frames. The ONU is synchronized with the GTC frame and attentively listens to the broadcast OLT frame with the upstream overhead PLOAM message. We can imagine the physical layer operation and administration and maintenance (PLOAM)-like channel, which is used for crucial settings of ONU by the OLT unit. This channel supports the activation process, encryption establishment and management. The message contains basic parameters, such as preassigned delay (delay can eliminate a different distance between OLT and ONU) and power level of ONU. OLT can send an extended burst length PLOAM message but depends on the presence of a reach extension (RE) element in the ODN. This element requires a power supply, backup power and B+ or C+ attenuation classes in the ODN. The RE element enables the limitation of the transmission convergence (TC) layer to be extended to the total length of an ODN or an increase in the split ratio; however, both have to comply with [38]. Note that the increase in the distance between OLT and ONU induces a higher complexity with an equalization delay allocation (we have to take into account the higher distance and the optical electrical optical (OEO) conversion in RE element. The upstream overhead PLOAM message and extended burst length message (optional) are transferred three times by OLT. Once the ONU receives and process a single upstream overhead PLOAM message (upstream overhead PLOAM message is not followed by an extended burst length message), the ONU loads and saves the included parameters (preamble and delimiter) and moves to the state O3. The second state is presented in Figure 8.

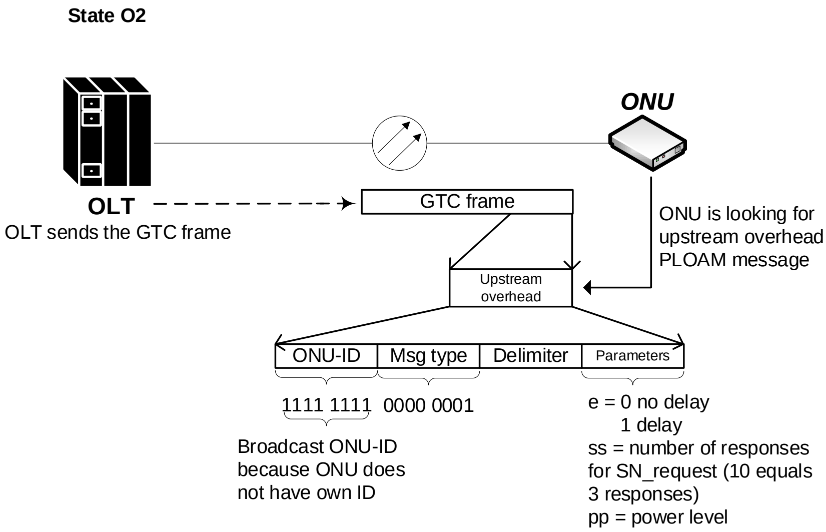

Figure 8. Activation process of ONU in a GPON network with PLOAM message details for state O2.

4.3. State O3—Serial Number State

The ONU knows the preamble and delimiter of the GTC frame at this time. OLT prepares a message series to obtain a serial number of the ONU. The first message is represented by an empty bandwidth map (BWmap) field (BWmap is a part of each downstream frame). OLT defines behavior—transmission start time and stop time—for a unique allocation identifier (Alloc-ID) by this field. OLT defines an allocation structure in transmission opportunities for the ONU in the ODN. Alloc-ID identifies a unique data recipient, which can be represented by transmission container (T-CONT). For example, T-CONT 1 carries voice over Internet protocol (VoIP) data with the highest priority) to assure a quiet window in the upstream direction. The quiet window defines a time (125 µs) during which ONUs cannot send any data. The OLT obtains 125 µs without data transferring. The first message contains Alloc-ID 0xFE, which is reserved for serial number requirements, and identifies some ONUs in the activation process. ONU also uses the same Alloc-ID in a response. The second message (Serial Number request) takes into account the key parameters: minimum-maximum ONU distance, 48 μs random delay, and 2 ± 1 μs response time of ONU. The last message with a half BWmap occupation finalizes the serial number request. Note that all mentioned messages are sent by OLT and represent unique request (Serial Number request). If the ONU processes all three messages, it prepares a response. The response is included in the Serial Number ONU PLOAM message (part of the upstream burst frame) with the following parameters: ONU identifier (ONU-ID) with value 1111 1111 because the ONU does not have a unique ONU-ID, message identifiers 0000 0001 (PLOAM message number), vendor ID (producer ID is defined by ANSI T1.220), unique serial number part of ONU (vendor-specific serial number) and preassigned delay. The OLT processes the response of the ONU (upstream burst with Serial Number ONU PLOAM message) and prepares an ONU-ID based on the provided information. The ONU-ID has 1 B size and can represent a maximum of 256 unique ONU-ID values. The ONU-ID range from 0 to 253 is considered for identification of ONU. ONU-ID 254 should not be assigned because the value corresponds to Alloc-ID (reserved for Serial number request), and ONU-ID 255 is a broadcast value. The selected ONU-ID value OLT sends to the ONU by the Assign ONU-ID PLOAM message three times. The Assign ONU-ID message has a broadcast ONU-ID identifier (1111 1111), message identification value (0000 0011), new ONU-ID for ONU in activation process (from range 0–253) and serial number identifier, which corresponds with a unique ONU. Once the ONU processes and saves a new ONU-ID, it can move to the state O4. The third state is presented in Figure 9 by three instances.

4.4. State O4—Ranging State

The main objective of this state is to replace the preassigned delay by an equalization delay. The equalization delay is calculated by OLT according to various distances between the OLT and ONUs. Three messages (ranging request, ranging response and ranging time PLOAM) are employed for this purpose. First, OLT sends a ranging request by GTC frame with an empty BWmap field (to obtain a quiet window 125 μs) addressed for a unique ONU (by ONU-ID), and Alloc-ID of the requirement is exactly the same as that of the ONU. OLT waits for an instant response. Immediately, the ONU responds by a serial number ONU PLOAM message. The message includes ONU-ID, vendor ID, vendor-specific serial number and delay equals 0 in this phase. The response does not contain any delay, and since OLT knows the sending time, an equalization delay is established based on this information. A new equalization delay value is transferred from OLT to the ONU by the ranging time PLOAM message. The ranging time message has a unique ONU-ID, message identification value (0000 0100), path type identifier (0—main path, 1—backup path) and new delay value, which is represented by bits. OLT sends a ranging time message three times. Once the ONU receives and adds a new equalization delay (preassigned delay was previously used), the ONU moves to the state O5. A new equalization delay value eliminates different physical distances between OLT and the ONUs. The virtual distance of each ONU is the same. We have to take into account the timer TO1 with the default value 10 s. This timer is initialized when the ONU enters the state O4. The timer represents a restriction for finalization of the ranging process. If the TO1 expires, the ONU moves to the state O2. Detailed passing of the ONU during state O4 is shown in Figure 10.

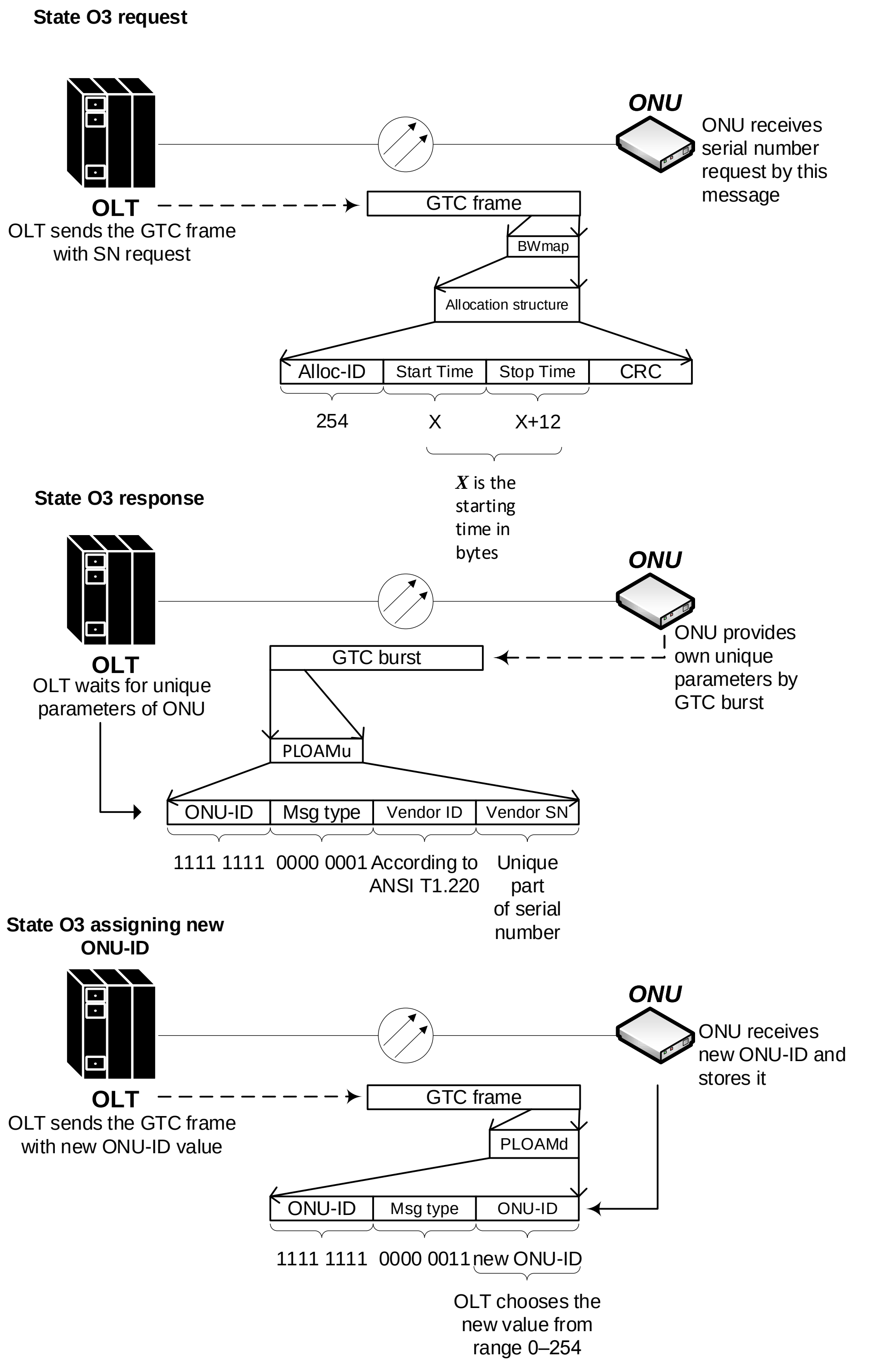

Figure 9. Activation process of ONU in a GPON network with PLOAM message details for state O3.

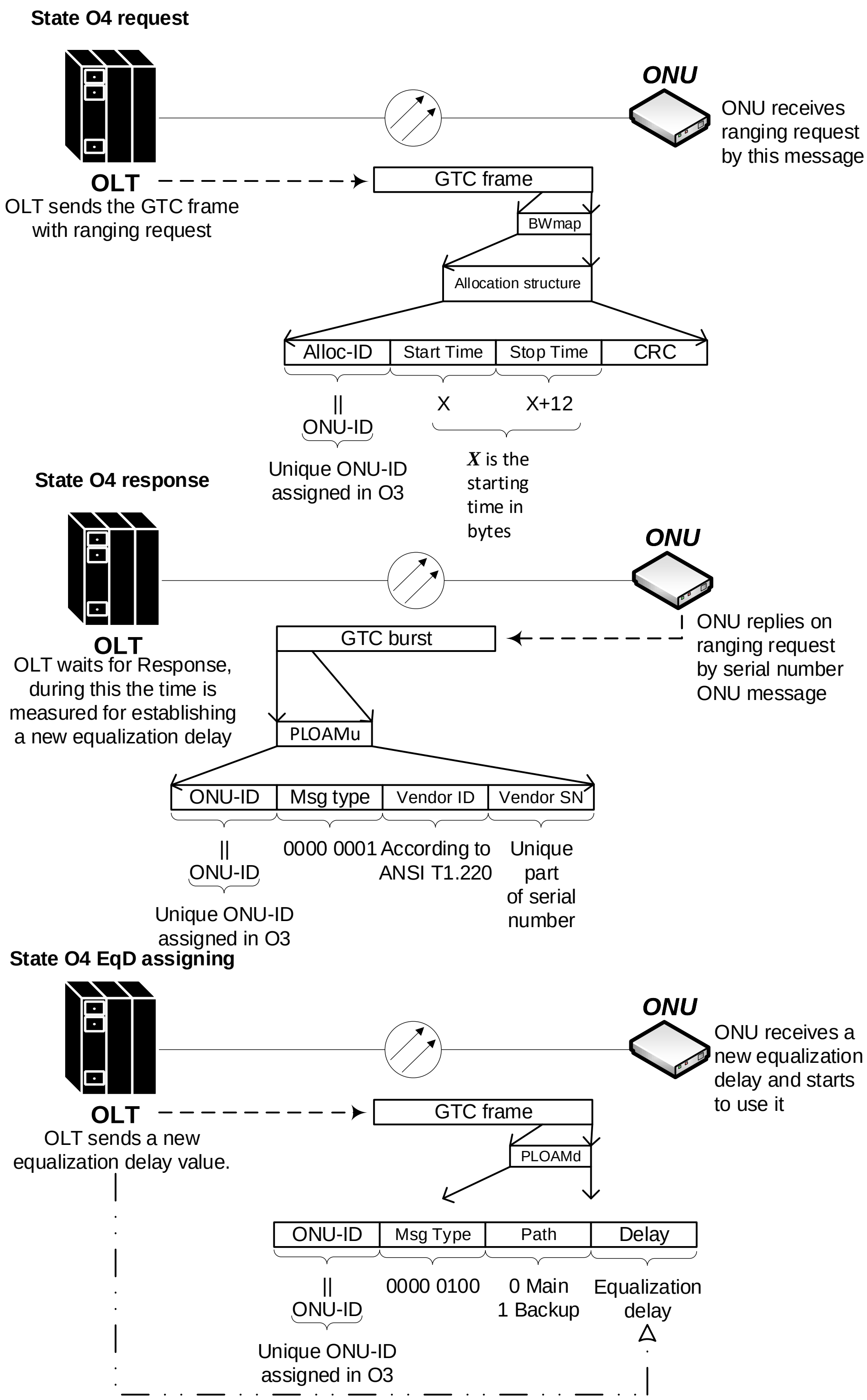

Figure 10. Activation process of ONU in a GPON network with PLOAM message details for state O4.

4.5. State O5—Operational State

An operation state is a finite state from a communication point of view. The ONU is able to transfer data (user data and control data in PLOAM messages) in the upstream direction. The ONU can obtain DBA grants for urgent data. Sometimes, the ONU can lose a frame/signal. If this situation occurs, the ONU moves to state O6 or can receive a deactivation/disable request of OLT. A deactivation request causes the ONU to move to state O2 but the LOS/LOF depends on the time TO2 value (We explain

TO2 in the state O6). The ONU moves to state O7 while a disable request is received. Bidirectional data communication is presented in Figure 11.

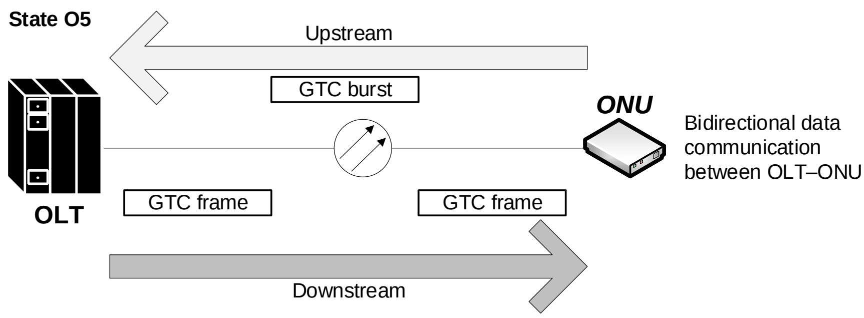

Figure 11. Activation process of ONU in a GPON network with PLOAM message details for state O5.

4.6. State O6—POPUP State

ONU can lose synchronization with GTC frames, which is identified by LOS/LOF alarms. If this situation occurs, the ONU stops data transmission and starts the timer TO2 (recommended initial value is 100 ms). During this time, the ONU attempts to achieve synchronization. The ONU searches for the synchronization pattern (0xB6AB31E0) in the GTC frame. If the ONU restores the synchronization and receives a directed/broadcast POPUP message of OLT, then it returns to state O5/O4; otherwise, it moves to state O1.

4.7. State O7—Emergency State

Sometimes, OLT needs to remotely turn off some ONUs (during maintenance). A disable serial number message with the option "disable" is used for this purpose (ONU recognizes its ONU-ID in message content). Once the ONU receives this message, it immediately stops data transmission and turns off a laser (OLT sends message three times). If the ONU does not turn off a laser after three messages, a hardware issue exists at the ONU unit. Only one solution is available: a technician worker has to manually turn off the ONU in a customer's apartment/house. OLT is able to remotely activate (after deactivation of the ONU) by the same message with the "enable" option. All ONU parameters are re-established during the activation process because the ONU enters state O2 after receiving this message with the "enable" parameter.

5. Conclusions

Fabry–Pérot lasers do not need temperature stabilization (cooling) and are significantly more inexpensive than DFB lasers. On the other hand, there are several limitations that hinder the application of this laser diode in optical networks with a low bitrate not higher than 2.5 Gbps and for shorter distances due to problems with low optical power and dispersions. FP lasers are used in APONs/BPONs, GPONs and EPONs in ONUs. FP lasers have also been used in WDM-PONs as wavelength-locked ONUs. DFB lasers are commonly used in most telecommunication devices for their single-longitudinal mode, narrowband line width and high-power optical signal. DFB lasers are used in all PON standards in OLT units, could be used in ONUs for APONs/BPONs, EPONs and GPONs, and must be used in the XG-PON, NG-PON2 and 10GEPON. In the second part of this tutorial, the activation process of an ONU was described. The main purpose of this tutorial is to provide information for a non-technical audience, enabling them to understand not only passive optical networks and their communication but also that it is necessary to activate ONUs before bidirectional communication can begin. We provided detailed information about each state regarding which end unit has to pass from the initial to the operational state, with PLOAM messages exchanged during these processes.

Author Contributions: Conceptualization T.H., P.M. and N.-H.B.; Investigation T.H. and N.-H.B.; Funding acquisition T.H.; Methodology T.H, P.M., and N.-H.B.; Project administration T.H. and P.M.; Resources T.H.; Supervision P.M. and N.-H.B.; Validation T.H.; Writing—original draft T.H., P.M., and N.-H.B. All authors have read and agreed to the published version of the manuscript.

Funding: Research described in this paper was financed by the grants of the Ministry of the Interior of the Czech Republic, Program of Security Research, VI20172020110, PID VI2VS/422 "Reduction of security threats at optical networks"; E-infrastructure CESNET—modernization, registration number CZ.02.1.01/0.0/0.0/16_013/0001797; and the National Natural Science Foundation of China (NSFC 61671092).

Acknowledgments: Tomas would like to give thanks to Ales Buksa for his support at the University in memorial. Ales has taught and inspired him with many things in his personal life.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Alloc-ID	Allocation identifier
APON	Asynchronous transfer mode passive optical network
ATM	Asynchronous transfer mode
AWG	Arrayed waveguide gratings
BPON	Broadband passive optical network
BWmap	Bandwidth map
CE	Coexistence element
CW	Continual wave
CWDM	Coarse wavelength division multiplex
DFB	Distributed feedback laser
DWDM	Dense wavelength division multiplex
EPON	Ethernet passive optical network
GPON	Gigabit passive optical network
GTS	Gigabit passive optical network transmission convergence
FP	Fabry–Pérot laser
IEEE	Institute of Electrical and Electronics Engineers
ISPs	Internet services provider
ITU-T	International Telecommunication Union Telecommunication sector
LOF	Loss of frame
LOS	Loss of signal
MLM	Multi longitudinal mode
ODN	Optical distribution network
OEO	Optical electrical optical
OLT	Optical line termination
ONU	Optical network unit
P2MP	Point-to-multipoint
PLOAM	Physical layer operation and administration and maintenance
PONs	Passive optical networks
RE	Reach extension
RMS	Root mean square
SML	Single longitudinal mode
T-CONT	Transmission container
TDM	Time division multiplexing
VoIP	Voice over Internet protocol
WDM	Wavelength division multiplex
WWDM	Wide wavelength division multiplex
XG-PON	Next-generation passive optical network

References

1. Harstead, E.; Veen, D.V.; Houtsma, V.; Dom, P. Technology Roadmap for Time Division Multiplexed Passive Optical Networks (TDM PONs). *J. Lightwave Technol.* **2018**, *37*, 657–664. [CrossRef]
2. DeSanti, C.; Du, L.; Guarin, J.; Bone, J.; Lam, C.F. Super-PON. *J. Opt. Commun. Netw.* **2020**, *12*, D66–D77. [CrossRef]
3. Horvath, T.; Munster, P.; Oujezsky, V.; Bao, N.H. Passive Optical Networks Progress: A Tutorial. *Electronics* **2020**, *9*, 1081. [CrossRef]
4. Zhang, D.; Liu, D.; Wu, X.; Nesset, D. Progress of ITU-T higher speed passive optical network (50G-PON) standardization. *J. Opt. Commun. Netw.* **2020**, *12*, D99–D108. [CrossRef]
5. Hussain, S.B.; Hu, W.; Xin, H.; Mikaeil, A.M. Low-Latency Dynamic Wavelength and Bandwidth Allocation Algorithm for NG-EPON. *J. Opt. Commun. Netw.* **2017**, *9*, 1108–1115. [CrossRef]
6. Mora, J.; Ortega, B.; Grassi, F.; Capmany, J. WDM Optical Access Network for Full-Duplex and Reconfigurable Capacity Assignment Based on PolMUX Technique. *Photonics* **2014**, *1*, 503–515. [CrossRef]
7. Mohammed, N.A.; Mansi, H. Performance Enhancement and Capacity Enlargement for a DWDM-PON System Utilizing an Optimized Cross Seeding Rayleigh Backscattering Design. *Appl. Sci.* **2019**, *9*, 4520. [CrossRef]
8. Khalili, H.; Rincón, D.; Sallent, S.; Piney, J.R. An Energy-Efficient Distributed Dynamic Bandwidth Allocation Algorithm for Passive Optical Access Networks. *Sustainability* **2020**, *12*, 2264. [CrossRef]
9. Rafiq, A.; Hayat, M. QoS-Based DWBA Algorithm for NG-EPON. *Electronics* **2019**, *8*, 230. [CrossRef]
10. Prat, J. *Next-Generation FTTH Passive Optical Networks*, 1st ed.; Springer: Dordrecht, The Netherlands, 2008.
11. G.983.1: Broadband Optical Access Systems Based on Passive Optical Networks (PON). Available online: https://standards.globalspec.com/std/103304/ITU-TG.983.1 (accessed on 18 June 2020).
12. 802.3ah-2004—IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment: Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks. Available online: https://ieeexplore.ieee.org/document/1337489 (accessed on 18 June 2020).
13. 802.3av-2009—IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment 1: Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks. Available online: https://ieeexplore.ieee.org/document/5294950 (accessed on 18 June 2020).
14. G.984.1: Gigabit-Capable Passive Optical Networks (GPON): General Characteristics. Available online: https://standards.globalspec.com/std/227301/itu-t-g-984-1 (accessed on 18 June 2020).
15. G.987.1: 10-Gigabit-Capable Passive Optical Networks (XG-PON): General Requirements. Available online: https://standards.globalspec.com/std/10046311/itu-t-g-987-1 (accessed on 18 June 2020).
16. G.989.1: 40-Gigabit-Capable Passive Optical Networks (NG-PON2): General Requirements. Available online: https://standards.globalspec.com/std/1641451/itu-t-g-989-1 (accessed on 18 June 2020).
17. Trevisan, M.; Giordano, D.; Drago, I.; Munafo, M.M.; Mellia, M. Five Years at the Edge Watching Internet From the ISP Network. *IEEE/ACM Trans. Netw.* **2020**, *28*, 561–574. [CrossRef]
18. Vos, B.D.; Duthilleul, F.; Fredricx, F.; Vetter, P.; Ossieur, P.; Bauwelinck, J.; Qiu, X.Z.; Vandewege, J.; Watte, J. Demonstration of extended split APON. In *Optical Fiber Communication Conference and Exhibit*; Opt Soc. America: Anaheim, CA, USA, 2002; pp. 437–439. [CrossRef]
19. Vetter, P.; Goderis, D.; Verpooten, L.; Granger, A. Systems aspects of APON/VDSL deployment. *IEEE Commun. Mag.* **2000**, *38*, 66–72. [CrossRef]
20. Williams, P.; Walker, R.; Charles, P.; Ogden, R.; Wood, A.; Carr, N.; Carter, A. Design and fabrication of monolithically integrated DFB laser-wavelength duplexer transceivers for TPON/BPON access links. *Electron. Lett.* **1991**, *27*, 809–810. [CrossRef]
21. Zhang, Z.; Guo, Q.; Ju, C.; Cai, S.; Wang, L.; Zhang, M.; Chen, X. Optical- and Electrical-Domain Compensation Techniques for Next-Generation Passive Optical Networks. *IEEE Commun. Mag.* **2019**, *57*, 144–150. [CrossRef]
22. El-Nahal, F.; Hanik, N. Technologies for future wavelength division multiplexing passive optical networks. *IET Optoelectron.* **2020**, *14*, 53–57. [CrossRef]

23. Yi, L.; Liao, T.; Huang, L.; Xue, L.; Li, P.; Hu, W. Machine Learning for 100 Gb/s/λ Passive Optical Network. *J. Lightwave Technol.* **2019**, *37*, 1621–1630. [CrossRef]
24. Van Veen, D.; Houtsma, V. Strategies for economical next-generation 50G and 100G passive optical networks [Invited]. *J. Opt. Commun. Netw.* **2020**, *12*, A95–A103. [CrossRef]
25. Lam, C.F. *Passive Optical Networks: Principles and Practice*, 1st ed.; Academic Press: Cambridge, MA, USA, 2013.
26. Muciaccia, T.; Gargano, F.; Passaro, V. Passive Optical Access Networks. *Photonics* **2014**, *1*, 323–346. [CrossRef]
27. Wang, X.; Gan, C.; Tong, L. Adaptive Scheduling Algorithm for the Coexistence of ONUs with Different Tuning Time in Virtual Passive Optical Network. *IEEE Photon. J.* **2019**, *11*, 1–8. [CrossRef]
28. Ruffini, M.; Ahmad, A.; Zeb, S.; Afraz, N.; Slyne, F. Virtual DBA virtualizing passive optical networks to enable multi-service operation in true multi-tenant environments. *J. Opt. Commun. Netw.* **2020**, *12*, B63–B73. [CrossRef]
29. Coldren, L.A.; Corzine, S.W.; Mashanovitch, M.L. *Diode Lasers and Photonic Integrated Circuits*, 2nd ed.; Wiley: Hoboken, NJ, USA, 2012.
30. Ujager, F.S.; Zaidi, S.M.H.; Younis, U. A review of semiconductor lasers for optical communications. In *7th International Symposium on High-Capacity Optical Networks and Enabling Technologies*; IEEE: Cairo, Egypt, 2010; pp. 107–111. [CrossRef]
31. Yla-Jarkko, K.; Grudinin, A. Performance limitations of high-power DFB fiber lasers. *IEEE Photon. Technol. Lett.* **2003**, *15*, 191–193. [CrossRef]
32. Das, B.K.; Ricken, R.; Quiring, V.; Suche, H.; Sohler, W. Distributed feedback–distributed Bragg reflector coupled cavity laser with a Ti:(Fe:)Er:LiNbO3 waveguide. *Opt. Lett.* **2004**, *29*, 165–167. [CrossRef] [PubMed]
33. Dutton, H. *Understanding Optical Communications*, 1st ed.; Prentice Hall: Upper Saddle River, NJ, USA, 1998.
34. Jin, X.; Chuang, S.L. Bandwidth enhancement of Fabry-Perot quantum-well lasers by injection-locking. *Solid State Electron.* **2006**, *50*, 1141–1149. [CrossRef]
35. Li, T.; Willner, A. *Optical Fiber Telecommunications V*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2008.
36. Horvath, T.; Munster, P.; Oujezsky, V.; Vojtech, J. Activation Process of ONU in EPON/GPON Networks. In *2018 41st International Conference on Telecommunications and Signal Processing (TSP)*; IEEE: Athens, Greece, 2018; pp. 1–5. [CrossRef]
37. Horvath, T.; Munster, P.; Oujezsky, V.; Vojtech, J. Activation Process of ONU in EPON/GPON/XG-PON/NG-PON2 Networks. *Appli. Sci.* **2018**, *8*, 1934. [CrossRef]
38. G.984.3: Gigabit-Capable Passive Optical Networks (G-PON): Transmission Convergence Layer Specification. Available online: https://standards.globalspec.com/std/2056269/ITU-TG.984.3 (accessed on 18 June 2020). [CrossRef]